

**Reliability and Cost Evaluation of
Small Isolated Power Systems Containing
Photovoltaic and Wind Energy**

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by

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ABSTRACT

Global application of renewable energy is growing rapidly due to enhanced public concerns for adverse environmental impacts and escalation in energy costs associated with the use of conventional energy sources. Photovoltaics and wind energy sources are being increasingly recognized as cost effective generation sources in both small and large electric power systems. A comprehensive evaluation of reliability and cost is required to analyze the actual benefits of utilizing these energy sources. The reliability aspects of utilizing renewable energy sources have largely been ignored in the past due the relatively insignificant contribution of these sources in major power systems, and consequently due to the lack of appropriate techniques.

Renewable energy sources have the potential to play a significant role in the electrical energy requirements of small isolated power systems. These systems are primarily supplied by costly diesel fuel. A relatively high renewable energy penetration can significantly reduce the system fuel costs but can also have considerable impact on the system reliability. Small isolated systems routinely plan their generating facilities using deterministic adequacy methods that cannot incorporate the highly erratic behavior of renewable energy sources. The utilization of a single probabilistic risk index has not been generally accepted in small isolated system evaluation despite its utilization in most large power utilities. Deterministic and probabilistic techniques are combined in this thesis using a system well-being approach to provide useful adequacy indices for small isolated systems that include renewable energy.

This thesis presents an evaluation model for small isolated systems containing renewable energy sources. The overall model is created by integrating simulation models that generate appropriate atmospheric data, evaluate chronological renewable power outputs and combine total available energy and load to provide useful system indices. A software tool SIPSREL+ has been developed which generates risk indices, well-being indices and additional energy based indices to provide realistic cost/reliability measures of renewable energy utilization in small isolated systems. The concepts presented and the examples illustrated in this thesis will help system planners to decide on appropriate installation sites, the types and mix of different energy generating sources, the optimum operating policies, and the optimum generation expansion plans required to meet increasing load demands in small isolated power systems containing photovoltaic and wind energy sources.

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**DEDICATED TO
MY BELOVED WIFE *ANUJA***

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LIST OF ABBREVIATIONS

Alternating Current	AC
Auto-regressive Moving Average	ARMA
Capacity Factor	CF
Capacity of the Largest Unit	CLU
Capacity of the Largest Unit in a State	CLUS
Capacity of the Smallest Unit	CSU
Capacity Outage Probability Table	COPT
Capacity Reserve	CR
Capacity Reserve Margin	CRM
Clearness Index	K _c
Composite Customer Damage Function	CCDF
Conditional Probability Capacity Outage Probability Table	CPCOPT
Current - Voltage	I-V
Daily Peak Load Variation Curve	DPLVC
Diesel Generator	DG
Direct Current	DC
Expected Energy not Supplied per Interruption	EENSPINT
Expected Energy Supplied	EES
Expected Health Duration	EHDUR
Expected Interruption Duration	EINTDUR
Expected Margin Duration	EMDUR
Expected Surplus Energy	ESE
Expected Unserved Energy	EUE
Forced Outage Rate	FOR
Frequency of Interruptions	F
Frequency of Margin	F(M)
Graphical User-Interface	GUI
Healthy State Probability	P(H)
Hierarchical Level	HL
Identification Number	ID#
IEEE-Reliability Test System	IEEE-RTS
Installed Capacity	IC
Interrupted Energy Assessment Rate	IEAR

Load Duration Curve	LDC
Loss of Energy Expectation	LOEE
Loss of Health Expectation	LOHE
Loss of Load Expectation	LOLE
Loss of Load Probability	LOLP
Loss of the Largest Unit	LLU
Marginal State Probability	P(M)
Maximum Power Point	MPP
Mean Time to Failure	MTTF
Mean Time to Repair	MTTR
Megabyte	MB
Megahertz	MHz
Megawatt-hour	MWh
Monte Carlo Simulation	MCS
Peak Load	PL
Peak Watt	W _p
Photovoltaic	PV
Reliability Test System	RTS
Small Isolated Power Systems	SIPS
System Minutes	SM
Units per Million	UPM
Unused Energy Ratio	UER
Wind to Diesel Energy Dispatch Ratio	W:D
Wind Turbine Generator	WTG

1. INTRODUCTION

1.1 Power System Reliability

The basic function of an electric power system is to satisfy the system load and energy requirements as economically as possible and with a reasonable assurance of continuity and quality [1]. The two aspects of relatively low cost electrical energy at a high level of reliability are often in direct conflict and present an important problem in determining an appropriate generating reserve capacity margin. Too high a value will result in an overly reliable system with excessive investment costs, while too low a value will yield a low cost system with poor service continuity. Better methods are continuously under study and development to help system planners decide the optimum investment in system facilities to meet the increasing demand with a reasonable level of reliability.

Power system reliability evaluation provides a measure of the overall ability of a power system to perform its intended function. The concept of reliability can be subdivided into two basic aspects: system adequacy and system security [2]. System adequacy relates to the existence of sufficient facilities within the system to satisfy the customer demands within the system operating constraints. System security relates to the ability of the system to respond to disturbances arising within the system. Reliability evaluation in this thesis is limited to the domain of adequacy assessment.

The basic techniques for adequacy assessment can be categorized in terms of their application to segments of a complete power system. A power system can generally be divided into three basic functional zones: generation, transmission and distribution.

Reliability evaluation can be conducted in each of these functional zones or in the combinations that define hierarchical levels [2] shown in Figure 1.1.

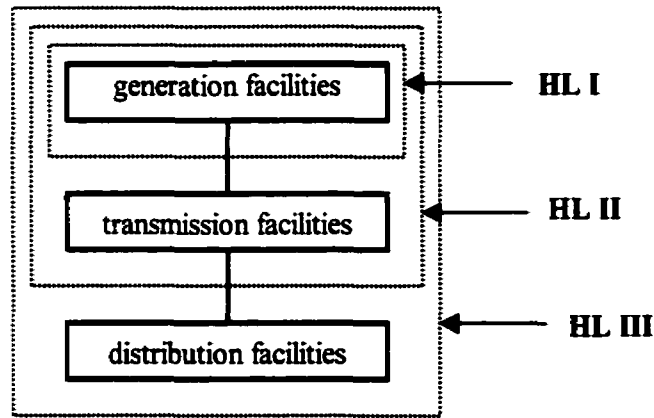


Figure 1.1: Hierarchical Levels in Adequacy Studies

Adequacy assessment at hierarchical level I (HL I) is concerned only with the generating facilities. Hierarchical level II (HL II) includes both generation and transmission facilities. Hierarchical level III (HL III) includes all three functional zones.

1.2 HL I Adequacy Study

HL I adequacy evaluation is concerned with assessing the ability of the generating facilities to satisfy the total system load demand and to have adequate capacity to account for random failures, load fluctuations and to perform corrective and preventive generating unit maintenance. The reliability of transmission and distribution systems and the ability to convey the generated energy to the consumer load points are not considered at this level. The basic system model in an HL I study is shown in Figure 1.2 and this study is usually termed as generating capacity reliability evaluation.



Figure 1.2: Basic Model for HL I Study

Reliability and cost studies in this thesis are focused on small isolated power systems (SIPS), which can be practically represented by HL I models. In many cases, a SIPS consists of a single generating plant with virtually no transmission and an extremely small and rather compact distribution system. Under these conditions, HL I adequacy is an important parameter in the overall system evaluation of a SIPS. Reliability evaluation in this thesis, is therefore, limited to the domain of HL I assessment of small isolated power generating systems.

1.2.1 Evaluation Techniques

HL I evaluation techniques are employed to determine the appropriate generating capacity required to ensure against excessive shortages and provide an acceptable level of adequacy. The available techniques can be broadly categorized into the conventional deterministic methods and the modern probabilistic approaches.

The deterministic or rule of thumb methods were the earliest techniques used to determine the required capacity reserve in a generating system. The common deterministic approaches require a system capacity reserve equal to a fixed percentage of the total installed capacity (IC), equal to the capacity of the largest unit (CLU), or equal to the sum of the two values.

The only available techniques in the past were deterministic, and electric power utilities used one of the methods discussed above to determine the required generating capacity. The basic weakness of a deterministic approach is that it does not incorporate any explicit recognition of the actual risk in the system. These methods cannot recognize the stochastic nature of component failures, of customer demands or of system behavior as a whole. The applications of these techniques rely on the subjective judgment of the system planning and operating personnel.

The need for probabilistic mathematical evaluation of the system risk based on stochastic system behavior has been recognized since at least the 1930s [1]. The effort in this area, over the last four decades, has resulted in the wide range of probabilistic techniques available today. Most modern large power utilities employ probabilistic methods in generating capacity adequacy assessment. The Loss of Load and the Loss of Energy methods are the widely used probabilistic techniques. Other methods include the Frequency and Duration technique. Appropriate adequacy indices can be evaluated to assess the system reliability using either direct analytical methods or using simulation techniques.

The Loss of Load Expectation (LOLE) [3] is the most widely used adequacy index. A loss of load is considered to occur when the forecast system load exceeds the system generating capacity. LOLE is measured in days per year or hours per year and is the expected number of days or hours in a year that the system generating capacity will be inadequate to satisfy the system load.

The Loss of Energy method provides indices which have a more physical significance than the Loss of Load indices, and can be directly related to the customer interruption costs [1]. Energy based indices are therefore receiving more attention, particularly in systems that have generating units with potential energy limitations [4]. Loss of Energy Expectation (LOEE) or Expected Unserved Energy (EUE) is the expected energy in

MWh (or kWh) that cannot be supplied by the system in a year. Units per Million (UPM) and System Minutes (SM) are other energy based indices used by utilities.

Frequency and duration methods are relatively complex and not generally used as basic adequacy criteria. The indices, however, provide valuable system information that is relatively easy to interpret. They can be estimated using simulation techniques to provide additional analysis of the system risk. Examples of the more useful frequency and duration indices are Frequency of Interruption, Expected Interruption Duration and Expected Energy Not Supplied per Interruption.

1.2.2 Criteria Used by Power Utilities

The methods adopted by major power utilities for generating capacity adequacy evaluation have gradually shifted from being deterministic to probabilistic over the last thirty years. Table 1.1 lists the reliability criteria used by Canadian utilities from the results of surveys [3] conducted in different years. Only one utility participating in the survey indicated that it used a probabilistic approach in 1964. Subsequent surveys indicated more utilities adopting probabilistic methods. In 1987, only one participating utility was still using a deterministic capacity reserve criterion but with supplementary checks for a probabilistic LOLE index.

Table 1.1: Criteria Used in Reserve Capacity Planning

Method	Criterion	Survey Date					
		1964	1969	1974	1977	1979	1987
Deterministic	Percent Margin	1	4	2	2	3	1*
	Loss of Largest Unit	4	1	1	1	-	-
	Combination of 1 and 2	3	6	6	6	2	-
	Other Methods	2	1	-	-	-	-
Probabilistic	LOLE	1	5	4	4	6	6
	EUE	-	-	-	-	-	2

* with supplementary checks for LOLE

The generating capacity adequacy criteria used by the participating utilities in the year 1987 are listed in Table 1.2. It can be seen that LOLE is the most common adequacy evaluation index. The Loss of Energy indices are also used by two utilities.

Table 1.2: Basic Criteria and Indices in 1987

Utility/System	Criterion	Index
BC Hydro and Power Authority	LOLE	1 day/10 yrs
Alberta Interconnected System	LOLE	0.2 days/yr
Saskatchewan Power Corporation	EUE	200 UPM
Manitoba Hydro	LOLE	0.1 day/yr
Ontario Hydro	EUE	25 SM
Hydro Quebec	LOLE	2.4 hours/yr
New Brunswick Electric Power Commission	CRM*	CLU or 20%PL
Nova Scotia Power Corporation	LOLE**	0.1 days/yr
Newfoundland and Labrador Hydro	LOLE	0.2 days/yr

* with supplementary checks for LOLE

** with supplementary checks for CRM

The main reasons for the reluctance to use probabilistic methods in the past were lack of data, limitations of computational resources, lack of realistic reliability techniques, aversion to the use of probabilistic techniques and a misunderstanding of the significance and meaning of probabilistic criteria and risk indices [1]. None of these reasons are valid today and, as a result, major power systems throughout the world widely apply probabilistic techniques in generating capacity planning.

1.3 Small Isolated Power Systems

A small isolated power system (SIPS) as considered in this thesis is a relatively small generating plant, situated at a remote site to serve a small community, with no possibility of interconnected assistance from a neighboring system. Table 1.3 shows the number of SIPS in Canadian utilities and their relative sizes [5].

Table 1.3: SIPS in Canadian Utilities

Utility	Number of SIPS	Total Installed Capacity (kW)	Size of Largest System (kW)	Size of Smallest System (kW)
Newfoundland Hydro	30	46,775	18,750	90
Hydro Quebec	21	56,000	11,200	550
Ontario Hydro	23	20,226	2,350	170
Manitoba Hydro	12	18,445	4,085	350
Saskatchewan Power	1	132	132	132
Alberta Power Ltd.	27	35,295	16,880	40
BC Hydro	9	35,550	9,420	1,850
NWT Power Corp.	47	188,000	52,560	70
Yukon Electrical	7	8,855	5,050	245

Despite the fact that large power utilities in Canada no longer utilize conventional rule of thumb methods for capacity assessment and exploit more responsive probabilistic techniques, SIPS still employ deterministic methods for adequacy evaluation. Table 1.4 lists the criteria used by SIPS in Canada as shown in a survey report published in 1995 [5].

Table 1.4: Criteria Used by SIPS

Utility	Deterministic Criterion
Newfoundland Hydro	CR = CLU
Hydro Quebec	CR = 90%CLU + 10%IC for plants with 5 engines or less CR = 90%CLU + 90%CSU + 10%IC for 6 engines or more
Ontario Hydro	CR = CLU
Manitoba Hydro	CR = 80%CLU + 20%IC
Saskatchewan Power	To strive for a safe and continuous supply of electricity.
Alberta Power Ltd.	CR = CLU CR = 90%CLU + 10%IC for remote sites
BC Hydro	CR = CLU
NWT Power Corp.	CR = CLU + 10% PL for PL < 3 MW CR = CLU + 5% PL for PL > 3 MW
Yukon Electrical	CR = CLU + 10% PL

CR = capacity reserve IC = installed capacity
 CLU = capacity of the largest unit
 CSU = capacity of the smallest unit
 PL = peak load

There are many reasons for the reluctance to apply probabilistic techniques to SIPS [6]. A major concern is the usual shortage of appropriate data on generating unit performance and on the actual load demand, as many sites do not have full time operating personnel or continuous load demand metering. There are also concerns about the ability to interpret a single numerical risk index such as the Loss of Load Expectation (LOLE) and the lack of system operating information contained in a single risk index. SIPS planners are used to capacity planning based on physical and observable reserve margins. The existing probabilistic risk indices, however, do not provide any assessment of the capacity reserve available during the course of system operation.

The data necessary for probabilistic evaluation should become available with time as many SIPS are making concerted efforts to collect appropriate information. The need for probabilistic techniques that take the existing deterministic criteria into account has been realized. A new probabilistic approach, known as System Well-being Analysis, has been developed [7] which can embed any specified deterministic criterion in a SIPS evaluation. A software tool SIPSREL [8] has also been developed that can be used to analyze the risk and well-being of a SIPS from various aspects. The well-being approach has been further modified in this research for application to SIPS that include renewable energy sources in addition to the conventional generating units.

1.4 Renewable Energy in Small Isolated Power Systems

The majority of SIPS, throughout the world, are supplied with diesel engine generators [5, 9]. Other forms of electrical power generation in SIPS are hydro, solar and wind energy conversion systems. Considerable attention has been given in recent years to renewable energy sources due to concerns with dwindling fuel reserves and the potential impact of conventional energy systems on the environment.

The application of these unconventional energy sources offers great appeal to satisfy energy demand at remote sites, where it is relatively expensive to run a transmission line from a distant electricity grid. Photovoltaic and wind technology is finding an increasing application as renewable energy sources in small isolated power systems. SIPS that include photovoltaic sources and/or wind energy sources in addition to the conventional generating sources are designated as Composite SIPS in this thesis.

1.4.1 Photovoltaic Power Generation

Photovoltaics is the direct conversion of sunlight into electricity. PV can produce clean, quiet, pollution free renewable energy that is accessible whenever there is regular sunshine. PV technology has developed rapidly over the past two decades – from a small scale, specialist industry supplying the U.S. space program to a broadly based global activity. The estimated annual worldwide production of solar photovoltaic cells is about 120 MW. up from only 40 MW in 1990 [10].

Solar cells are made up of materials, such as crystalline silicon, that exhibit a property known as the photovoltaic effect, which causes them to absorb photons of light and release electrons. This is the basis of PV technology. PV cells are assembled into modules. PV modules are further assembled in series or parallel configurations to form arrays that are erected on supports in the field as shown in Figure 1.3 [11]. The amount of power delivered by a PV cell is measured in peak watt (Wp).

A basic PV system consists of PV arrays that generate DC electricity. An inverter converts DC power to AC power which is then supplied to the system load. A maximum power point tracker can be used to adjust the PV voltage to operate at the maximum available power. Other common components of a PV system are control, switching and metering devices. PV system components, which are either too sophisticated or not

practical for use in systems that supply remote community energy needs, are not considered in this thesis. Energy storage is also not considered.

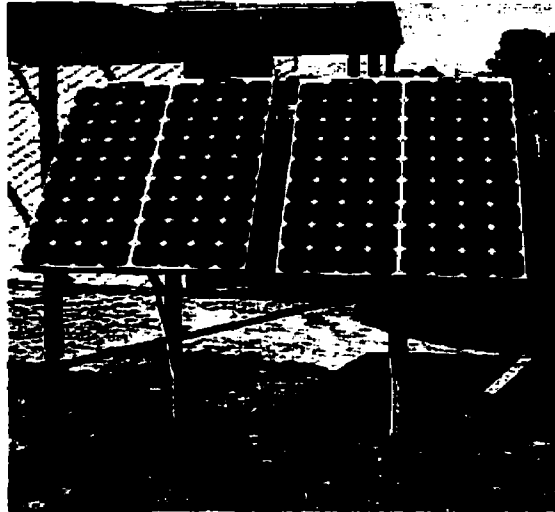


Figure 1.3: PV Arrays

PV installations have relatively high initial costs, and the incremental costs of increasing the supply are almost as high. The cost, however, continues to fall with the development of PV cells. Figure 1.4 [12] illustrates the decrease in the price of PV modules with time.

Many countries around the world have adopted energy policies that promote the extension of PV installations to meet energy demands. This is true in both the developed and the developing nations. The U.S. Department of Energy has launched a “Million Solar Roofs” program [13] to initiate businesses and communities to install solar systems on one million rooftops by 2010. A “Net Metering Bill” has passed the legislature in several states to encourage customers to use PV systems to run their utility meter backwards. A recent market study by the Utility PhotoVoltaic Group estimated a

potential U.S. domestic market for PV of 9000 MW at a system price of \$3 per Wp [13]. The Japanese government program for the solar industry offers subsidies of up to 50% of the total installation cost and aims to install 4,600 MW by 2010 [14]. Government support in countries such as Germany, Switzerland, and the Netherlands has given rise to some progressive plans for PV application in Europe. The European Energy Commission has targeted a PV installation of 3,000 MW throughout Europe by 2010. The increasing use of PV systems in developing countries is evident from the rapid expansion of sales of PV systems for household use. Sales have topped 10,000 in Sri Lanka, 60,000 in Indonesia, 150,000 in Kenya, 85,000 in Zimbabwe, 40,000 in Mexico and more than 100,000 systems in China. In all, a total of nearly a half a million PV systems have been sold in the developing countries [10].

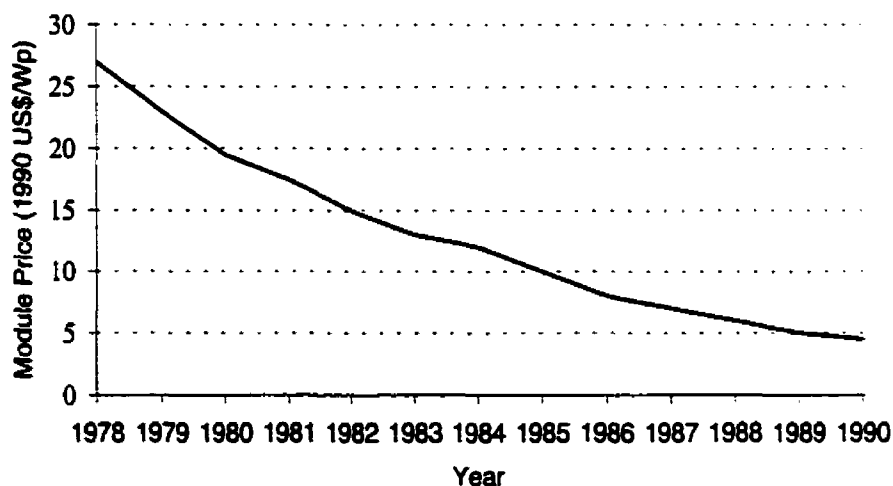


Figure 1.4: PV Price History

The actual benefits of PV energy in power generating systems can only be assessed by conducting relevant cost and reliability studies. There is considerable reluctance to consider PV sources as generation, rather than negative load, because there have been very few studies indicating the amount of conventional load that can be offset. The

adequacy assessment of a generating system including PV sources is a complex process which requires accurate forecasting of solar radiation and other dominant weather factors at the installation site, reliable modeling of PV arrays and their associated variables, and a technique to compare the intermittent energy availabilities to the system load.

1.4.2 Wind Energy Conversion Systems

The differences in atmospheric pressure created by the sun results in turbulent masses of air creating wind energy. Wind energy has become, under specific circumstances, competitive with conventional sources of electricity due to lower cost and improved technology. Over the past five years the capacity of wind turbines installed globally has been expanding at an average of 25% each year. From just 2,500 MW in 1992 it had jumped to 7,639 MW in 1997 and further to 10,153 MW by the end of 1998 [15].

The power output of a wind turbine generator (WTG) depends on randomness and chronological variability of wind velocity. Wind is highly variable, site-specific and also terrain specific. It has instantaneous, minute by minute, hourly, diurnal and seasonal variations. There is a non-linear relationship between the available wind speed and the electric power produced by a wind energy conversion system. There are many different types of commercially available WTG ranging from less than 1 kW to more than 3 MW in capacity. Research and development continues in wind turbine technology to achieve higher energy efficiency and power quality at a lower cost. It is desirable to select a WTG that is best suited for a particular site and for the intended consumption pattern in order to achieve maximum overall benefit.

A WTG is mounted on a tower, the height of which depends on the capacity of the unit. The main components are the rotating blades, a gearbox, an electric generator and a controller. Figure 1.5 shows a WTG [15]. The site where one or more wind turbines are installed is known as a wind farm or a wind park.



Figure 1.5: A Wind Turbine Generator

Wind power has been the fastest growing energy source. An active public awareness to reduce global warming has encouraged industrialized countries to use wind energy. Wind power produces virtually no carbon dioxide, the main greenhouse gas, and is one of the cheapest renewable sources. Many large industrial companies have shown interest in the development of wind technology and have made massive investments already. Wind turbines have been an ideal choice in developing nations where the most urgent need is to feed basic electricity into rural or isolated areas without any power infrastructure. Predictions are that wind energy will continue to expand at an impressive rate of over 20% each year. It is forecast that worldwide capacity will have reached 20,000 MW by 2002 [14].

In order to determine the potential benefits associated with wind as a possible energy option, assess the effect of WTG on system reliability, and provide quantitative indicators for making system planning decisions, it is both necessary and important to develop comprehensive adequacy evaluation techniques which include wind energy systems.

1.5 Research Objectives

In recent years, escalation in the cost of energy derived from fossil and nuclear fuels, and enhanced public awareness of the potential impact on the environment of conventional energy systems has created an increased interest in the development and utilization of alternate sources, such as wind and solar energy. The application of these unconventional energy sources appear to be most cost effective when providing basic energy needs to small communities located in remote isolated areas.

Wind energy and PV systems require no fuel and can, therefore, be included in conventional SIPS to offset costly diesel fuel. Diesel generators operate most efficiently at rated output. The fuel cost increases when a diesel system is run continuously to supply a widely varying load. The associated maintenance cost is also relatively high and is a factor of operating time. The cost of transporting fuel to remote locations and providing storage is quite significant in many cases. New policies, formulated to reduce global warming, associate penalties with the use of fuels that emit greenhouse gases. The use of local renewable energy sources will also relieve many SIPS utilities around the world from having to depend on imported fuel.

There are apparent cost benefits in including PV arrays and wind turbines in SIPS since costly fuel is replaced by free renewable energy. It is, however, important to assess the amount of benefit and the key variables that dictate or affect the economics involved. Another very important aspect is to evaluate the impact on system reliability. It is quite evident that limitations in the energy available from renewable sources and their intermittent behavior degrade system reliability. Reducing cost at the expense of reliability is not a benefit. The analysis of cost/benefit due to the application of PV and wind energy is incomplete without a corresponding reliability assessment.

The previous section notes that the application of PV and wind energy has grown rapidly over the past few years and is expected to accelerate in the future. The development in

PV and WTG technology, the continuous decrease in their cost, and the uncertainty and increase in fuel prices in the future, are some of the important factors that contribute to the growth of solar and wind energy conversion systems. Prevailing public environmental concerns have led to worldwide governmental policies that promote the use of PV and wind energy. Support for these renewable energy sources are overwhelming, both in the industrialized and in the developing countries. Photovoltaic and wind energy conversion systems have, as a result, been promoted with considerable fervor in which the practicalities of cost and reliability have largely been ignored. It is important to assess the inclusion of these technologies in SIPS, on both their technical and economical merits.

There has not been significant work in the past in the area of reliability evaluation of power systems that include PV and wind energy. Limited literature is available in HL-I adequacy studies of injecting PV or wind energy in large conventional systems. These studies have not been considered of much practical importance since the impact of a small unconventional energy penetration is negligible in a conventional system. Past research has tended to represent renewable energy sources by equivalent conventional units that can then be included in conventional reliability methods. A WTG unit is usually considered as either a multi-state unit [16, 17, 18] or an energy-limited unit [19]. These techniques lack satisfactory consideration of the random nature of important energy variables and their chronology and, therefore, do not provide a realistic assessment. Analytical techniques in PV analysis [20, 21] do not provide satisfactory results because of the random nature of cloud cover. There has also been some work done using Monte Carlo simulation [22, 23, 24, 25, 26]. Considerable research is still required in this area in order to provide acceptable evaluation techniques for practical implementation.

PV and WTG sources have mainly been utilized in meeting the energy requirements of remote isolated consumers. Adequacy assessment of SIPS is a special case where existing techniques that are useful to larger interconnected systems are not applicable.

The reliability and cost analysis of composite SIPS requires considerable research on appropriate adequacy modeling techniques in addition to compatible modeling of weather characteristics and the corresponding energy conversion methodology.

The basic objective of the research described in this thesis was to investigate the potential benefits of utilizing renewable energy sources (PV and WTG) in SIPS in regard to cost and reliability. System planners and operators require definitive methodologies and practical tools that provide objective indicators to help them make appropriate decisions in optimum planning and operation of composite SIPS.

The development of appropriate methods to conduct reliability and cost evaluation of different types of composite SIPS was the primary objective of the research. Analytical and simulation techniques were previously developed [7] to evaluate the adequacy of conventional SIPS using practical system indices. The development of the system well-being approach used the previous work to incorporate the inclusion of PV and wind energy sources in conventional SIPS. Appropriate modeling of the site-specific atmospheric conditions, the energy conversion by PV arrays and WTG characteristics have been implemented in the overall developed simulation techniques. Useful system indices that specifically reflect the energy-limited, intermittent behavior of the renewable sources have been incorporated for cost and reliability evaluation of composite SIPS.

The development of an evaluation tool, which can implement the different models developed for various tasks into one integrated framework and can be used with ease for adequacy and cost studies on composite SIPS, was another objective of the research. The methodologies to evaluate the different system indices have been incorporated in a graphical user-interface software tool named SIPSREL+. The tool has been developed using an object-oriented approach that facilitates incremental development in a cyclic process and can be easily modified and extended for further development and future applications.

An important objective of the research was to examine how the evaluation tool can be utilized to analyze the effects of various system parameters on the evaluation of cost and reliability of composite SIPS. The effects of variation in system load, the penetration levels of PV and wind energy sources, the forced outage rates (FOR) of conventional and unconventional units, the operating constraints and geographical site selections have been compared for SIPS of different compositions. The objective was not to explore all possible system studies but to examine selected practical situations and to provide clear explanation of the utility of the results obtained. The information obtained from such studies can be used in decision making in composite SIPS planning and operation.

The overall objective of the research was to provide methodologies and tools to conduct a wide range of system studies that can help system planners and operators decide on the appropriate installation site, type and amount of unconventional energy to include in SIPS, the optimum operating policies, the comparison of alternative schemes in capacity expansion and many other issues related to the cost and worth of planned activities in composite SIPS. With these objectives in mind, the overall research activities were conducted in the following stages:

1. Modeling and development of adequacy assessment techniques for composite SIPS
2. Examining the reliability characteristics of composite SIPS
3. Examining the costs associated with composite SIPS
4. Integration of the developed methodologies for reliability and energy assessment into an integrated tool for analyzing composite SIPS

1.6 General Overview of the Thesis

The rapid growth of photovoltaics and wind energy applications and their immense potential in the future dictates the need to seriously consider the quality of supply that can be obtained and the associated cost benefits that can be achieved. Appropriate

techniques have been developed to forecast relevant weather data at the system location, to model PV arrays and WTG characteristics, and to conduct overall adequacy assessment of composite SIPS.

The developed evaluation method uses Monte Carlo simulation to simulate hourly weather conditions, energy outputs from renewable sources, and chronological comparisons of system generation and energy demand. The conventional adequacy assessment methods and the system well-being approach have been modified to incorporate renewable energy sources that are energy limited and intermittent in nature. The developed methodologies are implemented in a graphical user-interface software package named SIPSREL+ which can evaluate useful cost and adequacy indices for different types of composite SIPS.

Chapter 1 introduces the basic concepts related to the adequacy evaluation of SIPS and the existing problems. The growing application of PV and wind energy throughout the world is discussed along with the problems in assessing the benefits from their use in composite SIPS.

Chapter 2 describes the different reliability evaluation techniques that can be applied to SIPS. The problems with the existing deterministic and probabilistic methods are discussed and a new approach known as system well-being analysis is introduced. The chapter presents the basic concepts required in applying the well-being approach in Monte Carlo simulation and describes the advantages of this approach over the analytical techniques in the reliability evaluation of a composite SIPS.

Chapter 3 presents the development of an evaluation model for reliability assessment of a composite SIPS. The chapter describes the models developed to simulate the necessary atmospheric data, to convert the available solar and wind energy into electrical energy, and to simulate the system operation to obtain the adequacy and energy indices.

Chapter 4 describes the software tool SIPSREL+ that integrates the different evaluation models together in a user-friendly platform that can be used to conduct cost and reliability studies on different types of composite SIPS. The use of the integrated tool is demonstrated by application to a large practical power system. Studies analyzing the convergence criteria required for the simulation tool to efficiently obtain the desired accuracy are also described in this chapter.

Chapter 5 illustrates the effects of various system parameters on the system adequacy indices and on the cost related energy indices. The effects of the generating system configuration, the FOR of the energy sources, load levels, operating constraints and geographical system locations are analyzed by applying the evaluation tool to a practical example system.

Chapter 6 compares the different reliability evaluation techniques that are applicable to a composite SIPS to determine the most appropriate method to use in capacity planning. A dual criteria method that jointly uses both the health and risk indices is presented as an appropriate technique for generation expansion of a composite SIPS. A method to assess the capacities of renewable energy sources is also described in this chapter.

Chapter 7 provides useful indicators to assist in the selection of different types of energy sources, their penetration levels and the appropriate installation times in expansion schemes for a composite SIPS. A method to compare a number of different expansion schemes to obtain the optimum expansion plan is illustrated with an example. The effects of different variables on optimum capacity planning are also discussed.

The final chapter, Chapter 8, summarizes the thesis and highlights the conclusions.

2. RELIABILITY TECHNIQUES FOR SMALL ISOLATED POWER SYSTEMS

2.1 Introduction

Reliability evaluation of small isolated power systems (SIPS) is mainly focused on generating capacity adequacy evaluation since the transmission and distribution systems are often not significant. The previous chapter notes that probabilistic methods have largely replaced deterministic techniques in large modern power utilities. In spite of their widespread application in large systems, probabilistic methods are not generally applied to SIPS and these systems use the conventional deterministic approaches in capacity planning. The system well-being technique is a new approach to bring the deterministic and probabilistic methods together and provide a practical solution to the adequacy problems encountered in SIPS.

This chapter describes the various methods that can be applied to adequacy studies of SIPS. The different methodologies are illustrated with examples. The basic indices used to provide quantitative information on various measures of system adequacy are introduced.

2.2 Probabilistic Techniques

The basic approach to evaluating generating capacity adequacy consists of three parts; the generation model, load model and the risk model [1] as shown in Figure 2.1. The generation model and the load model are combined to obtain suitable risk indices.

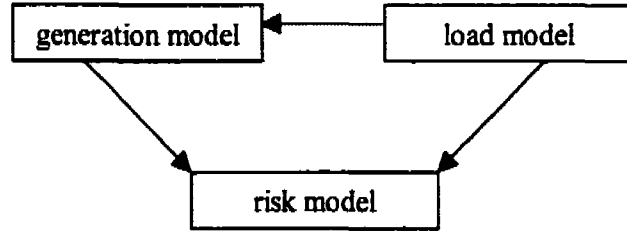


Figure 2.1: Basic Concepts in HL I Evaluation

The generating unit Forced Outage Rate (FOR) [1] is a basic parameter in generating capacity adequacy evaluation. It is defined as the probability of finding the unit on forced outage at some distant time in the future. It can be calculated using Equation (2.1):

$$\text{FOR} = \frac{\sum[\text{down time}]}{\sum[\text{down time}] + \sum[\text{up time}]} \quad (2.1).$$

The generation model used in most analytical techniques is an array of capacity levels and the associated probabilities of existence, and is known as a Capacity Outage Probability Table (COPT). The table can be obtained by adding the generating units recursively using Equation (2.2) [1]:

$$P(X) = \sum_{i=1}^n p_i * P'(X - C_i) \quad (2.2)$$

where $P'(X)$ and $P(X)$ denote the cumulative probabilities of the capacity outage state of X kW before and after the unit is added respectively. The above expression is initialized by setting $P'(X) = 1.0$ for $X \leq 0$ and $P'(X) = 0$, otherwise.

The load model incorporates the variation in system load level with time within a certain period. The basic period used in system planning is a calendar year. Different load models can be used depending on the availability of load data and the type of evaluation required. Analytical methods use the Daily Peak Load Variation Curve (DPLVC) or the Load Duration Curve (LDC). Simulation techniques normally use chronological load variation curves.

The generation model is combined with a particular load model to evaluate the desired risk indices. Figure 2.2 illustrates the method of convolving the COPT with the LDC to evaluate the loss of load and loss of energy indices.

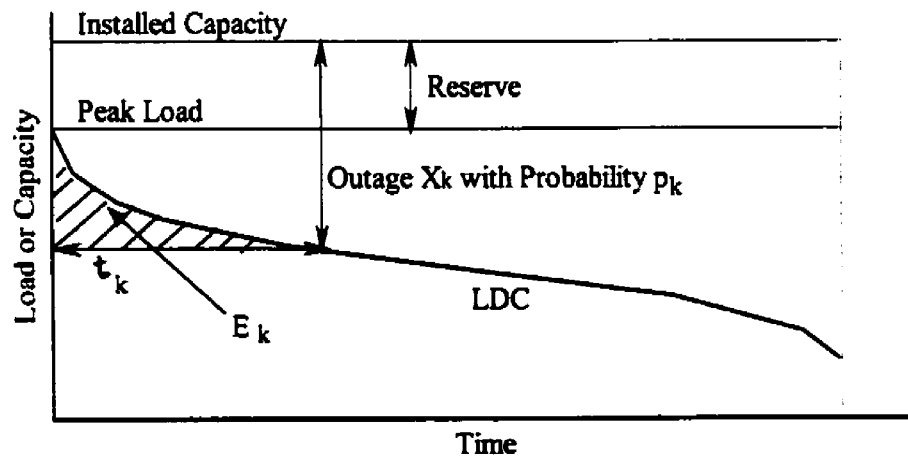


Figure 2.2: Evaluation of Risk Indices

Figure 2.2 shows that when an outage X_k , with probability p_k , exceeds the reserve, it causes a load loss for a time t_k . Each outage state X_k , with probability p_k , is superimposed on the load model and the time t_k for each load loss event is calculated. The Loss of Load Expectation (LOLE) is given by Equation (2.3) [1]:

$$LOLE = \sum_{k=1}^n p_k \cdot t_k \quad (2.3)$$

where n = number of capacity outage states in the COPT
 p_k = individual probability of capacity outage X_k
 t_k = load loss occurring time due to outage X_k .

If the time t_k is in per unit of the total time period, Equation (2.3) gives the Loss of Load Probability (LOLP) instead of the LOLE. The unit of LOLE is in days per year or hours per year depending on whether a DPLVC or a LDC is used respectively as the load model.

The area under the LDC, in Figure 2.2, is the total energy (E) demanded by the system in a year. When an outage X_k with probability p_k exceeds the reserve, it causes an energy curtailment E_k . Each outage state X_k in the COPT, with probability p_k , is superimposed on the LDC and the energy curtailed E_k for each load loss event is calculated. The energy based indices of Loss of Energy Expectation (LOEE), Units per Million (UPM) and System Minutes (SM) are obtained using the following equations [27]:

$$LOEE = \sum_{k=1}^n E_k \cdot p_k \quad (2.4)$$

$$UPM = \frac{LOEE}{E} \cdot 10^6 \quad (2.5)$$

$$SM = \frac{LOEE}{PL} \cdot 60 \quad (2.6).$$

The LOLE technique is illustrated using a practical SIPS example of three 500 kW and one 1000 kW diesel generating units. The FOR is assumed to be 5% for all the units. The system load is represented by a straight-line LDC with a load factor of 60% and a peak load of 1000 kW. The COPT for the system is shown in Table 2.1. Figure 2.3 illustrates the combination of the generation and the load model. The calculation of the loss of load indices is illustrated in Table 2.2.

Table 2.1: Capacity Outage Probability Table for the Example System

Capacity In (kW)	Capacity Out (kW)	Individual Probability	Cumulative Probability
2500	0	0.81450625	1.0
2000	500	0.12860625	0.18549370
1500	1000	0.04963750	0.05688750
1000	1500	0.00688750	0.00725000
500	2000	0.00035625	0.00036250
0	2500	0.00000625	0.00000625

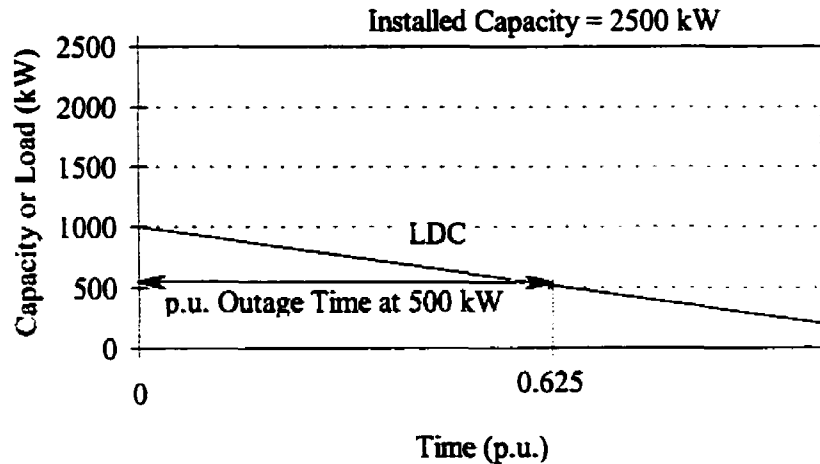


Figure 2.3: Combining Generation and Load Models

Table 2.2: Calculating the LOLP by the COPT Method

Cap In (KW)	Individual Probability	Outage Time (p.u.)	C2 * C3
2500	0.81450625	0	0
2000	0.12860625	0	0
1500	0.04963750	0	0
1000	0.00688750	0	0
500	0.00035625	0.625	0.000223
0	0.00000625	1	0.000006
LOLP =			0.000229

Considering 8760 hours in a year, $LOLE = LOLP * 8760 = 2.006$ hours/year.

The most widely used criterion is the LOLE. A LOLE of 0.1 days/year or 2.4 hours/year is a normal criterion used by Canadian utilities [3]. A reasonable adequacy criterion for a system in a developing country might be in the order of a LOLE of 2 days/year [28]. These techniques, however as discussed in Chapter 1, have not been accepted in SIPS.

2.3 Deterministic Techniques

The basic criteria used in adequacy evaluation of SIPS are deterministic. These techniques evaluate the system adequacy by measuring the amount of capacity reserve in a system. Different criteria are used to define an acceptable level of system reliability. The following are the common deterministic approaches.

1. Percent Margin or Capacity Reserve Margin (CRM):

The capacity reserve requirement is a fixed percentage of the total installed capacity. The system reliability is unacceptable when the capacity reserve is less than the specified value.

2. Loss of the Largest Unit (LLU):

The capacity reserve requirement is at least equal to the capacity of the largest unit. This approach prevents load curtailment due to an outage of any single generating unit. This criterion can be extended to include the loss of more than one unit.

3. Loss of the Largest Unit plus a Percent Margin:

The capacity reserve is equal to the capacity of the largest unit plus a fixed percentage of either the peak load or the total installed capacity. This method anticipates an outage of any generating unit together with fluctuations in forecast load.

A deterministic technique normally applied to a SIPS can, in general, be represented by Equation (2.7):

$$CR \geq CLU + x * PL \quad (2.7)$$

where CR = capacity reserve
CLU = capacity of the largest unit
and PL = peak load.

The multiplication factor x is normally between 0 – 15% depending on the judgment of the planner and on past experience. The Loss of the Largest Unit (LLU) criterion is the case when $x = 0$.

The installed capacity of the example system in the previous section is 2500 kW and the peak load is 1000 kW. The capacity reserve (CR), is therefore, $2500 - 1000 = 1500$ kW. The capacity of the largest unit (CLU) is 1000 kW. The system reliability is acceptable from a LLU criterion, since the CR is greater than the CLU. The criterion will be violated when the peak load exceeds 1500 kW.

The capacity requirement in SIPS planning is largely decided based on the deterministic measure of the system capacity reserve, which is the total installed capacity less the

system peak load. The variation in load with time, the shape of the load curve or the load factor, which have a profound effect on the system reliability, have no impact in the adequacy assessment using deterministic methods. These techniques cannot assess the effects of generating unit FOR, unit derated capacity states, energy limitations, unit maintenance schemes, or any uncertainties in forecast generation or load parameters. Deterministic methods cannot be applied to obtain optimum investment decisions, planning strategies or operating policies.

2.4 System Well-being Techniques

The deterministic and probabilistic approaches can be combined into a single framework [6] to alleviate some of the concerns expressed by SIPS planners, designers and operators regarding the use of a single risk index such as LOLE. This approach is known as System Well-being Analysis and is described in Figure 2.4 in terms of healthy, marginal and at risk states.

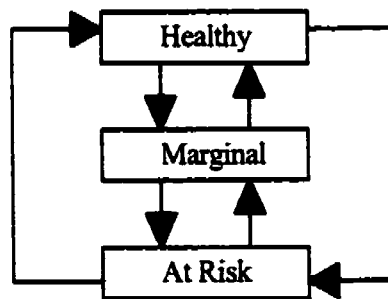


Figure 2.4: System Well-being Model

A combination of the basic deterministic and probabilistic concepts can be created through the definition of the system operating states. A system operates in the healthy

state when it has enough capacity reserve to meet a deterministic criterion such as the LLU. This can be extended to include more than one unit, or the largest unit plus a fixed margin. The system is not in any difficulty but does not have sufficient margin to meet the specified deterministic criterion in the marginal state. In the at risk state, the load exceeds the available capacity.

System well-being analysis can embed an acceptable deterministic criterion in a probabilistic approach. In this approach, probabilistic techniques are used to evaluate the magnitudes of the system capacity reserves, which are then compared to an accepted deterministic criterion, such as the LLU, in order to measure the degree of comfort in the system. Indices have been developed that can be used to assess a system from a deterministic aspect in addition to recognizing its stochastic behavior and inherent risks. An appreciation of the deterministic criterion that drives the probabilistic well-being indices makes these indices easily interpreted by SIPS planners who are more accustomed to a deterministic approach.

The basic well-being indices are the probabilities of health, margin and risk. The actual risk associated with the inability of the generating system to satisfy the load requirement is measured by the probability of being in the at risk state, which is termed the Loss of Load Probability (LOLP). The degree of comfort associated with operating the system within the accepted deterministic criterion is given by the probability of residing within the healthy state or the Healthy State Probability $P(H)$. The Marginal State Probability $P(M)$ is the probability of finding the system in a state that violates the deterministic criterion but is not in any difficulty. Well-being indices are also referred to as health indices. Frequency and duration health indices are also presented in this thesis. Since the LOLE is the most widely used risk index, a health index, with similar characteristics for the purpose of comparative adequacy studies, is introduced. The health index, the Loss of Health Expectation (LOHE) [7], is the expected duration in a year that the system does not meet the accepted deterministic criterion. It can be calculated using Equation (2.8):

$$\text{LOHE} = [1 - P(H)] * \text{Total Period in hrs or days (h/yr or d/yr)} \quad (2.8).$$

Conventional deterministic techniques make use of the CLU to determine the amount of capacity reserve needed in order to meet the accepted adequacy criterion. The CLU is the capacity of the largest unit in the system. In system health analysis, the required amount of capacity reserve is determined by the capacity of the largest operating unit at a particular point in time. The capacity of the largest unit in a state (CLUS) can be different for different generation system states. The CLUS is equal to the CLU only when the largest unit in the system is in the operating state.

The system reserve is compared with the CLUS throughout the total period of study to identify the operating health, margin and at risk states in a system well-being analysis. Both analytical and simulation techniques can be used to evaluate well-being indices. The analytical methods use direct mathematical models to evaluate the well-being indices and are discussed in the next sections. The Monte Carlo Simulation (MCS) technique is also described and can be used to provide distributions of the basic indices and the frequency and duration health indices.

The research work on the development of appropriate reliability evaluation techniques applicable to SIPS has led to several technical publications [6, 29 – 34]. These papers illustrate how the existing deterministic criteria can be used in combination with probabilistic techniques that recognize random system behavior and can be practically applied to SIPS adequacy problems.

Reference [6] describes the application of probabilistic techniques to SIPS and presents the system well-being approach. The paper illustrates the calculation of the basic well-being indices using the Contingency Enumeration Approach, which is further described in Section 2.4.1. The effects of different system parameters on the system health and risk are compared in the paper to demonstrate the ability of the well-being approach to respond to

stochastic system behavior. The healthy state probability is proposed as an appropriate criterion for adequacy studies in a SIPS that conventionally uses a deterministic criterion.

Reference [31] presents a dual criteria method that uses a combination of risk and health indices in SIPS capacity planning. The unit size and composition of the system, the size of the new units to be added and the accepted system criterion play a significant role in determining whether the risk index or the health index is the more restrictive index at any point in time. Using only one of the two criteria in driving the capacity planning may violate the other accepted criterion. Using both the indices will ensure that the system is acceptable from both aspects. The paper concludes that capacity planning using both the LOLE and the LOHE criteria can prove useful in practical applications to SIPS.

Reference [29] presents a new analytical approach known as the Conditional Probability COPT (CPCOPT) Method to evaluate the well-being indices. The paper illustrates the methodology of the new technique and describes how it can be used in the assessment of system capacity reserves. The CPCOPT method is compared with the conventional contingency enumeration approach to illustrate the advantages of the new technique. The new technique is more efficient in computation time and space requirement and can therefore also be applied to larger systems to evaluate well-being indices. The method is further described in the Section 2.4.2.

Reference [34] describes the application of MCS in well-being analysis. The paper illustrates the utilization of a simulation technique to estimate the average values and the distributions of the basic well-being indices and additional frequency and duration indices. The distributions of the well-being indices indicate the degree of variability and their likelihood in a given year. The frequency and duration indices provide useful information about the expected state residence times and the number of occurrences of different degrees of system comfort. The MCS method makes it possible to conduct an in depth analysis of a system using the well-being approach. Section 2.5 discusses the application of MCS in well-being analysis.

References [30, 32, 33] illustrate the results of various sensitivity studies that show the response of well-being techniques of various random variables and system parameters that influence the reliability of SIPS.

2.4.1 Contingency Enumeration Approach

The basic well-being indices can be evaluated using the Contingency Enumeration approach which utilizes a generation model in the form of an array that lists all the different possible combinations of the existing generating unit outages, their probabilities and the capacity of the largest unit associated with each contingency state (CLUS). A generating system, which has 'n' generating units that can reside in 'm' states, will have a total of m^n number of contingencies in the array model. A constant load level is used as the basic load model in this approach. If the annual peak load is used, the indices obtained are known as the annualized indices. A load duration curve can be used in the load model by dividing it into a number of discrete load levels. An accurate representation of the actual load curve will require a large number of load steps.

The contingencies in the generation model array are listed in an organized way, starting from the lower order to the higher order outages. Very high order contingencies are often neglected when the system has a large number of generating units. Each listed contingency is compared with the corresponding system load to determine the amount of capacity reserve available at each condition. A contingency is designated as healthy when the available reserve is equal to or more than the CLUS. When the available reserve is less than the CLUS but greater than zero, the contingency is considered to be marginal and when it is less than zero, the contingency is said to be at risk. The Healthy State Probability is the summation of all the individual probabilities for which the contingencies are healthy. The summation of all the individual probabilities during which the contingencies are marginal and at risk are the Marginal State Probability and Loss of Load Probability respectively.

The evaluation process is illustrated in Table 2.3 using the example system from Section 2.2.

Table 2.3: Contingency Enumeration Array

Units Out	Probability	Cap In (KW)	CLUS (KW)	Reserve (KW)	Health	Margin	Risk
None	0.81450625	2500	1000	1500	x	-	-
1	0.04286875	1500	500	500	x	-	-
2	0.04286875	2000	1000	1000	x	-	-
3	0.04286875	2000	1000	1000	x	-	-
4	0.04286875	2000	1000	1000	x	-	-
1,2	0.00225625	1000	500	0	-	x	-
1,3	0.00225625	1000	500	0	-	x	-
1,4	0.00225625	1000	500	0	-	x	-
2,3	0.00225625	1500	1000	500	-	x	-
2,4	0.00225625	1500	1000	500	-	x	-
3,4	0.00225625	1500	1000	500	-	x	-
1,2,3	0.00011875	500	500	-500	-	-	x
1,2,4	0.00011875	500	500	-500	-	-	x
1,3,4	0.00011875	500	500	-500	-	-	x
2,3,4	0.00011875	1000	1000	0	-	x	-
1,2,3,4	0.00000625	0	0	-1000	-	-	x
Total =					0.985981	0.013656	0.000363

The system health, margin and risk probabilities as shown in Table 2.3 are 0.985981, 0.013656 and 0.000363 respectively. The LOHE is calculated to be 122.80 h/yr using Equation (2.8). The application of the contingency enumeration method in well-being analysis of SIPS is illustrated [6, 29].

The generation model becomes very cumbersome in terms of memory space, computation time and also in terms of developing a general program applicable to all system types when a large number of generating units exist in the system or generating units with multiple states are involved. The unwieldiness of the above approach increases when a practical load curve is considered in the analysis.

2.4.2 Conditional Probability COPT Method

A new approach designated as the Conditional Probability COPT (CPCOPT) method has been developed to overcome some of the limitations of the Contingency Enumeration approach. The steps involved are shown in Figure 2.5. In this approach, the Risk State Probability or the LOLP is evaluated using the conventional COPT method described in Section 2.2. The Healthy State Probability is then evaluated by a similar technique in which several COPT are developed using the conditional probabilities of the available states of the largest units, and are convolved with the load curve. The sum of the healthy and risk state probabilities are then subtracted from unity to obtain the Marginal State Probability.

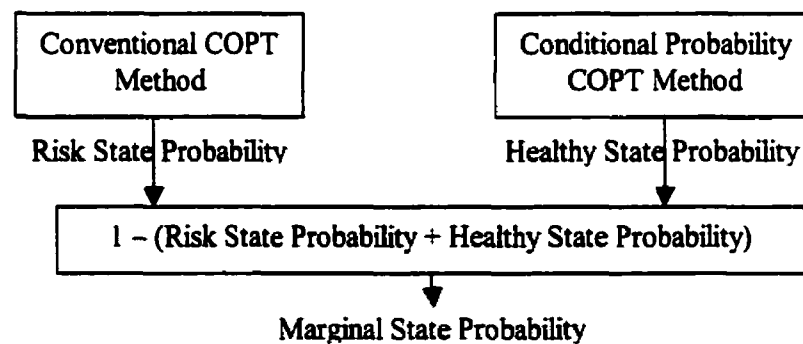


Figure 2.5: Steps involved in the New Analytical Method

The new method is illustrated using the example system from Section 2.2. In the first step, the LOLP is calculated as shown in Table 2.2, and is equal to 0.00029.

The second step is to evaluate the $P(H)$ using the conditional probability method. The COPT is convolved with the LDC to calculate the per unit duration of the total period for which the available reserve is equal to or greater than the CLUS at each capacity level.

Figures 2.6 and 2.7 illustrate the application given that the largest unit (1000 kW) is out, and the largest unit is in respectively.

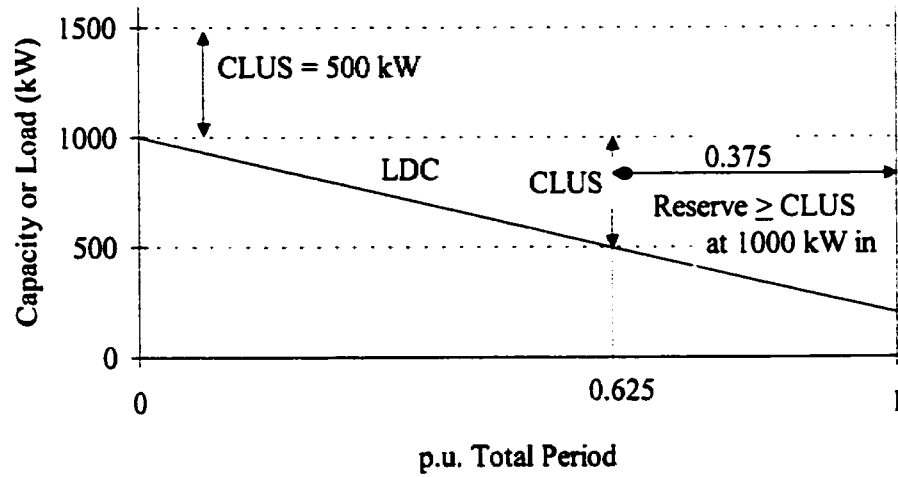


Figure 2.6: Capacity and Load Conditions Given that the 1000 kW Unit is Out

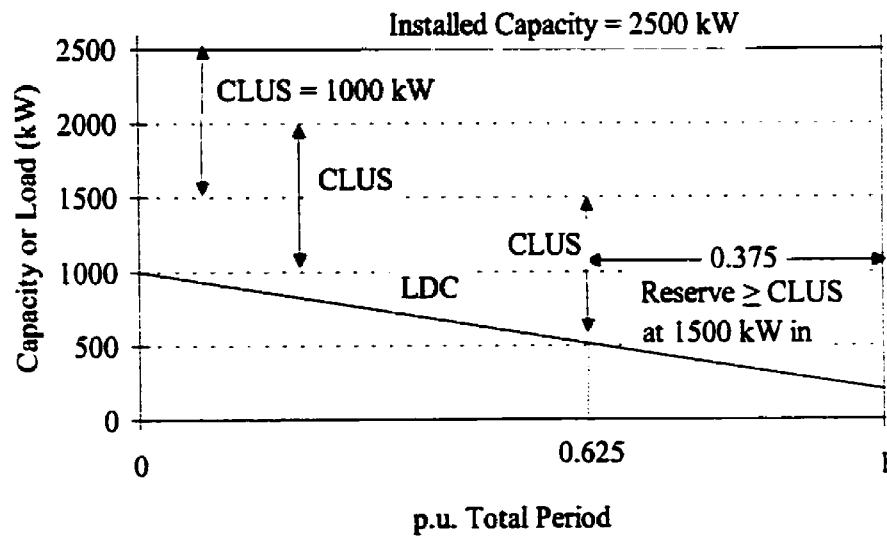


Figure 2.7: Capacity and Load Conditions Given that the 1000 kW Unit is In

Table 2.4 illustrates the calculation of the Healthy State Probability. The $P(H)$ is first evaluated for each condition. The system $P(H)$ is obtained by summing the products of each individual calculation and the corresponding conditional probability.

Table 2.4: Calculating the $P(H)$ Using the CPCOPT Method

Capacity In (KW)	Individual Probability	<u>Given 1000 kW unit Out</u> $x = 0$ KW CLUS = 500 KW		<u>Given 1000 kW unit In</u> $x = 1000$ KW CLUS = 1000 KW	
		Reserve \geq CLUS Time (p.u.)	C2 * C3	Reserve \geq CLUS Time (p.u.)	C2 * C5
$x + 1500$	0.857375	1	0.857375	1	0.857375
$x + 1000$	0.135375	0.375	0.050766	1	0.135375
$x + 500$	0.007125	0	0	0.375	0.002672
$x + 0$	0.000125	0	0	0	0
		$P(H) = 0.908141$		$P(H) = 0.995422$	

$$\begin{aligned}
 P(H) &= P(H)_{1000 \text{ kW out}} * P(1000 \text{ kW out}) + P(H)_{1000 \text{ kW in}} * P(1000 \text{ kW in}) \\
 &= 0.908141 * 0.05 + 0.995422 * 0.95 = 0.991058
 \end{aligned}$$

The final step is to calculate the Marginal State Probability by subtracting the sum of LOLP and $P(H)$ from 1.

$$\begin{aligned}
 P(M) &= 1.0 - P(H) - \text{LOLP} \\
 &= 1.0 - 0.991058 - 0.000229 = 0.008713
 \end{aligned}$$

The system health, margin and risk probabilities are 0.991058, 0.008713 and 0.000229 respectively. The LOHE is 78.33 h/yr. The details of the CPCOPT method are described in Reference [29].

The new method is similar to the conventional COPT method and has distinct advantages over the Contingency Enumeration approach in evaluating the system health

indices. The generation model in the new approach is a COPT that can be built by a recursive technique and has fewer capacity levels than an enumeration array. The new method is also very flexible in terms of easily incorporating a load model of any shape.

The biggest advantage of the CPCOPT technique comes from a truncation method that increases the computation efficiency tremendously and yet produces the health indices with high accuracy. This is accomplished by recognizing only the few largest units in the system that may become the CLUS for comparison with the reserve in order to determine the healthy states during the evaluation process. For example, in a system that has more than 10 generating units, it is sufficient to recognize only the largest four as the CLUS. The fifth largest unit becomes the CLUS only when the four largest units in the system fail simultaneously. The probability of the system then being healthy is practically insignificant, and the probability of the four largest units being simultaneously unavailable is extremely small. The accuracy can, however, be increased as desired by recognizing more units as the probable CLUS.

2.5 Monte Carlo Simulation Techniques

The adequacy evaluation methods described in the previous sections are analytical techniques that evaluate the indices using numerical solutions from a mathematical model that represents the system. Monte Carlo Simulation (MCS) provides another approach to estimate the indices by simulating the actual process and random behavior of the system [34]. Generally, MCS requires a large amount of computing time and is not used if direct analytical methods are available. MCS can however include system effects that may not be possible in a direct analytical approach without excessive approximation. MCS may be the only practical technique for certain systems that include a large number of random variables that are related in various ways. Another advantage of MCS is that it can be used to provide the distributions associated with the adequacy indices.

In the simulation approach, the operation of a power system is simulated chronologically from one hourly event to another for a calendar year. Each hourly event is examined for changes in load and the failure and repair of generating units. Each system state is defined in terms of the available margin, which is the difference between the available capacity and the load. The required adequacy indices are calculated by summing up the hourly values. The yearly samples are repeated a large number of times for accuracy in the expected results. The main steps in the MCS technique include building the generation model, combining the generation model with the chronological hourly load model, and then generating the desired indices and their distributions.

2.5.1 Generation Model

Generating unit mean times to failure (MTTF) and mean times to repair (MTTR) are the basic parameters in developing the generation model in the MCS technique. The MTTF of a unit is the expected time it remains in the available state before it fails. The MTTR is the expected time in the unavailable state until it is restored to the available state. The available, or up time, and the unavailable, or down time, are both assumed to be exponentially distributed in these studies and are calculated respectively using Equation (2.9) and Equation (2.10) [35]:

$$\text{Up Time} = \text{MTTF} \cdot \ln X_1 \quad (2.9)$$

$$\text{Down Time} = \text{MTTR} \cdot \ln X_2 \quad (2.10)$$

where X_1 and X_2 are random numbers between 0 and 1.

A state history consisting of a series of random up and down times for each individual unit can be generated with respect to time for a period of one calendar year. The required generation model combines the outage histories of all the units in the system for a desired period of time.

The application of MCS in system well-being analysis and the generation of useful indices are described in Reference [34]. The generation model that can be used to evaluate both the conventional risk indices and the health indices is shown in Figure 2.8. The model contains the outage history of the total capacity accompanied by the history of the total capacity less the corresponding CLUS at each capacity state.

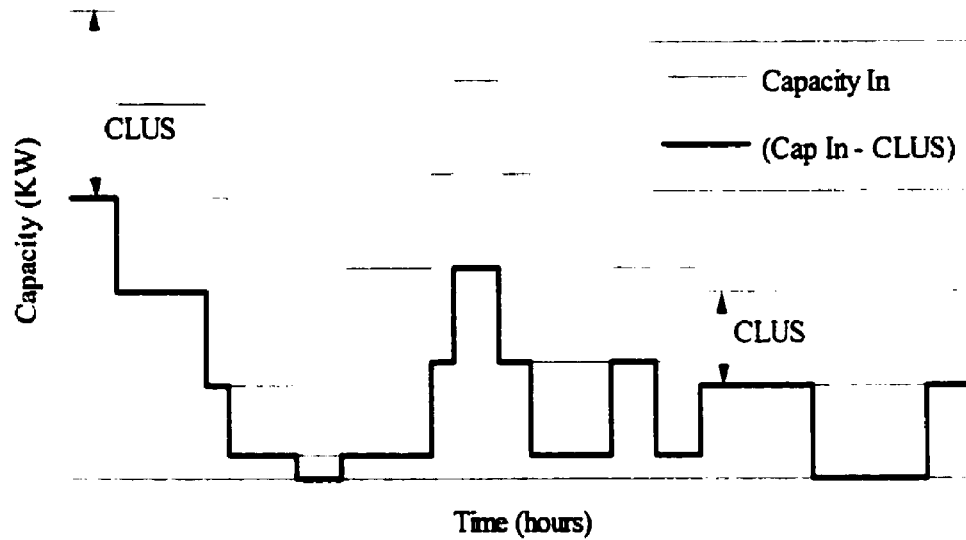


Figure 2.8: Generation Model for MCS

2.5.2 Combining the Generation and Load Models

The generation model is combined with the load model to obtain the adequacy indices. The required load model is the chronological hourly load in which it is assumed that the load changes discretely every hour and is constant throughout the hour. The capacity reserve at each hour is calculated and compared to the corresponding CLUS by superimposing the generation model on the load model as shown in Figure 2.9.

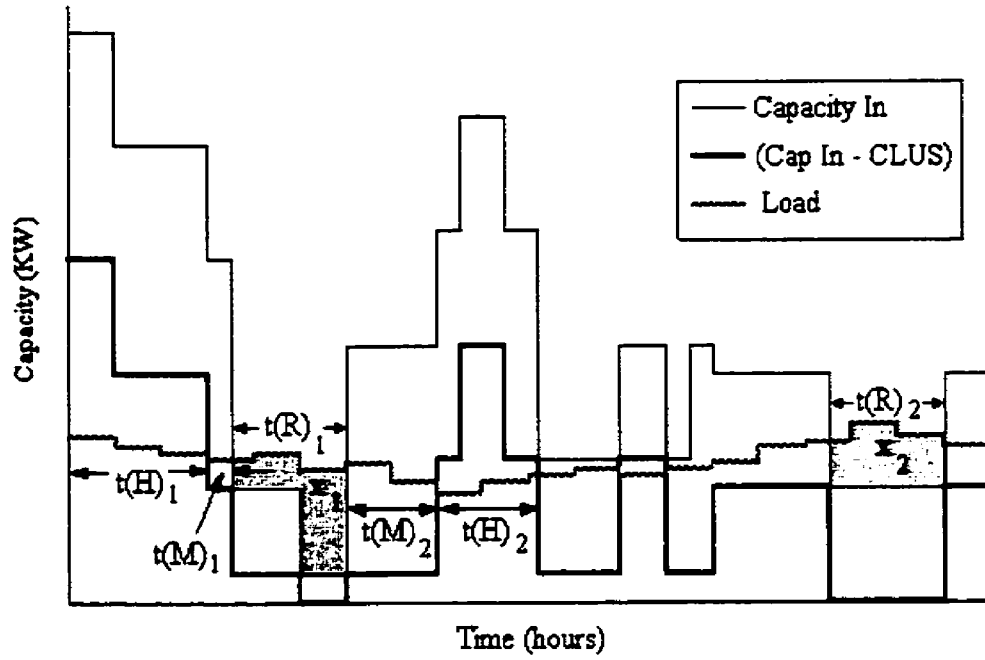


Figure 2.9: Combining Generation and Load Models

The conventional probabilistic risk indices are calculated by recording the duration ' $t(R)_i$ ' of each ' i^{th} ' curtailment, energy loss ' x_i ' at each curtailment, and the total number of load curtailments ' n ' as shown in Figure 2.9. The risk indices are then obtained using Equations (2.11-2.15).

$$\text{Loss of load expectation, LOLE} = \frac{\sum_{i=1}^n t(R)_i}{N} \quad (\text{h/yr}) \quad (2.11)$$

$$\text{Loss of energy expectation, LOEE} = \frac{\sum_{i=1}^n x_i}{N} \quad (\text{kWh/yr}) \quad (2.12)$$

$$\text{Frequency of interruptions, } F = \frac{n}{N} \text{ (int/yr)} \quad (2.13)$$

$$\text{Expected interruption duration, EINTDUR} = \frac{\sum_{i=1}^n t(R)_i}{n} \text{ (hr/int)} \quad (2.14)$$

$$\text{Expected energy not supplied per interruption, EENSPINT} = \frac{\sum_{i=1}^n x_i}{n} \text{ (kWh/int)} \quad (2.15)$$

where N = total number of simulated years.

Hourly data can also be recorded and used to evaluate the system well-being indices. Whenever the load profile is less than or equal to the corresponding '*Cap In – CLUS*' profile (as illustrated in Figure 2.9), the system states are healthy and the duration ' $t(H)_i$ ' for each of these healthy states is calculated. On the other hand, whenever the load profile is less than or equal to the '*Capacity In*' profile but greater than '*Cap In – CLUS*' profile (Figure 2.9), the states are marginal and the duration ' $t(M)_i$ ' for each of these marginal states is calculated. When the load profile is greater than the '*Capacity In*' profile, the conditions are risk states. The total number of healthy states, ' $n(H)$ ' and marginal states ' $n(M)$ ' are recorded in order to calculate the health indices using Equations (2.16-2.22) [34]:

$$\text{Loss of health expectation, LOHE} = \text{Year in hrs} - \frac{\sum_{i=1}^{n(H)} t(H)_i}{N} \text{ (h/yr)} \quad (2.16)$$

$$\text{Healthy State Probability, } P(H) = \frac{\sum_{i=1}^{n(H)} t(H)_i}{N * \text{Year in hrs}} \quad (2.17)$$

$$\text{Marginal State Probability, } P(M) = \frac{\sum_{i=1}^{n(M)} t(M)_i}{N * \text{Year in hrs}} \quad (2.18)$$

$$\text{Risk State Probability, LOLP} = \frac{\sum_{i=1}^{n(R)} t(R)_i}{N * \text{Year in hrs}} \quad (2.19)$$

$$\text{Frequency of margin, } F(M) = \frac{n(M)}{N} \text{ (margin/yr)} \quad (2.20)$$

$$\text{Expected health duration, EHDUR} = \frac{\sum_{i=1}^{n(H)} t(H)_i}{n(H)} \text{ (hr/health)} \quad (2.21)$$

$$\text{Expected margin duration, EMDUR} = \frac{\sum_{i=1}^{n(M)} t(M)_i}{n(M)} \text{ (hr/ margin)} \quad (2.22)$$

The frequency and duration health indices provide additional useful information about the system adequacy. The Frequency of Margin measures the expected number of times the marginal states are encountered in a year. In other words, it is the number of occurrences when the system is on the brink of failure. The Expected Health Duration measures the average duration of the system in the healthy state. A high value of the Expected Health Duration represents a more comfortable system at the same Healthy State Probability as it implies that the system slips away from the healthy state less often. The Expected Margin Duration is the average duration of the system in a marginal state. For the same Marginal State Probability, the Frequency of Margin and the Expected Margin Duration are inversely related. As to which of the two indices should be considered for a higher degree of system comfort is entirely dependent on the operating policies.

2.5.3 Simulation Time Requirements

A major limitation of the MCS method is the amount of required computing time, since the accuracy in the results improves with the number of yearly samples. It is necessary to determine the most appropriate time to stop the simulation in order to reduce the simulation time and yet obtain a reasonable confidence in the results. There are different stopping rules that can be used to track the convergence of the simulation process.

A common stopping rule involves observing the Sample Weight Plot [35] in which the average value of some variable of interest is plotted against the number of simulation samples. The LOEE has the least tendency to converge when compared to the other adequacy indices [36] and should, therefore, be taken as the variable to check for convergence. The Sample Weight Plot should stabilize as the simulation approaches convergence as shown in Figure 2.10. When the average value of the LOEE ceases to change significantly, the simulation is considered to have converged and should be terminated.

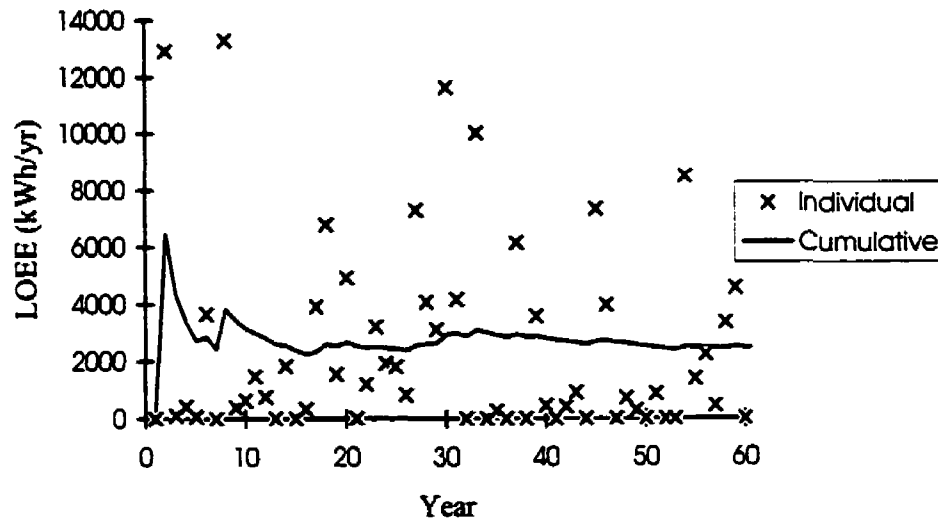


Figure 2.10: Sample Weight Plot

It is necessary to check for convergence at the end of each simulated year to find the most appropriate time to stop the simulation. The method involves calculating the deviation in the LOEE from the previous year. When the deviation percentage is within the specified tolerance and this situation continues successively for the specified number of years, the simulation is considered to have converged. A minimum and a maximum number of simulated years are usually specified to prevent premature convergence and non-converging situations respectively.

2.6 Conclusion

Reliability techniques applicable to practical power systems have undergone continuous development over the last fifty years. The application of these techniques vary widely in practice and depend largely on the type of power system. The existing probabilistic methods widely used in large inter-connected systems have not been considered applicable to SIPS. Most SIPS use deterministic approaches that cannot recognize the random behaviors inherent in a power system. System well-being concepts combine the deterministic and probabilistic methods and should prove useful to SIPS. The methodologies involved in the different basic adequacy evaluation techniques are briefly described in this chapter.

The basic procedure in a probabilistic approach is to convolve the generation model and the load model to obtain the risk model. The LOLE is the most widely used conventional risk index and is generally evaluated using the analytical COPT method. SIPS planners have concerns about using a single risk index such as the LOLE even though it provides a qualitative measure of the system risk. The common deterministic criteria include LLU, Percent Margin or a combination of the two methods.

System well-being analysis creates a bridge between the deterministic and probabilistic methods and defines indices that may be useful in practical adequacy assessment of

SIPS. The well-being indices can be evaluated using a Contingency Enumeration approach. A new analytical method known as the Conditional Probability COPT method has been developed which is very efficient with respect to computation space and time.

Analytical methods make use of direct mathematical models. The system under study is often simplified using practical approximations to fit into the model. These methods are generally employed to calculate the expected values of the basic adequacy indices. MCS techniques can be used to provide distributions and additional frequency and duration indices with relative ease. MCS can be used to obtain both conventional risk indices and well-being indices.

The MCS technique generally requires a large computation time. It is, however, very useful when the system under evaluation becomes too complex for analytical techniques. The accuracy of the mathematical models and the validity of the approximations that are made in analytical methods should be verified by comparing the results with an evaluation in which all the factors in the system are considered. MCS is a practical approach to evaluate the effect of including renewable energy sources in SIPS due to the inherent complexities of modeling the random weather variables, modeling the energy conversion, and conducting compatible adequacy evaluation.

3. DEVELOPMENT OF THE EVALUATION MODEL FOR COMPOSITE SMALL ISOLATED POWER SYSTEMS

3.1 Introduction

Renewable energy generation has received considerable attention in recent years due to concerns with environment preservation issues associated with conventional energy generation and the escalation in the cost of energy derived from them. The rapid growth of photovoltaics and wind energy conversion systems around the world over the past few years and the increasing attraction to these energy sources bolstered by governmental policies, public support and continuous technology development has been discussed in Chapter 1. It is clearly evident that the contribution of PV and wind energy systems to global energy requirements will increase with time.

The actual benefits of utilizing unconventional energy sources, such as PV and WTG, can only be quantitatively analyzed by relevant reliability and cost evaluation. These energy sources convert the energy available in the natural atmospheric condition at the system location into electric energy that can be utilized to satisfy various needs. It is, therefore, necessary to recognize the atmospheric variables that determine the amount of renewable energy available, and their effect on the energy conversion phenomenon in order to evaluate the amount of useful electrical energy that can be obtained from the unconventional sources. The available energy from these sources must be compared with the corresponding energy demand, while considering random system behavior, to evaluate the system adequacy. The adequacy evaluation of a renewable energy system is done in three major steps as shown in Figure 3.1.

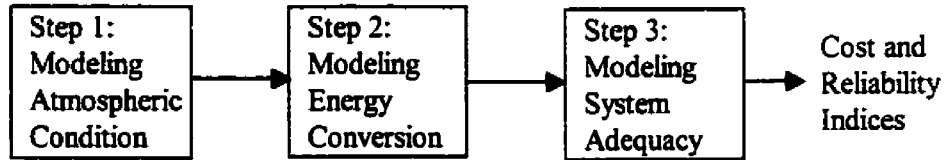


Figure 3.1: Renewable Energy Evaluation Steps

The first step involves the modeling of the time-varying atmospheric condition that dictates the amount of renewable energy that can be extracted from nature at the system location. Future hourly data are predicted using weather forecasting techniques based on historical data of the variables of interest (such as the wind speed, ambient temperature, solar radiation) for the specific site. The hourly values of these variables indicate the amount of renewable energy that can be harnessed at various points in time. The intermittent nature of the available energy depends on the random variation of the weather parameters, the inter-dependence in the variables and the auto-correlation in their variation.

Renewable energy conversion devices are modeled in the second step to evaluate the actual electrical energy that can be generated at the selected location. The synthetic weather data generated from the model in the first step are used as the input parameters for the second step. The interaction of the hourly weather data with the parameters of the energy conversion device is modeled to evaluate the electrical energy generated as a function of time.

The final step is the adequacy evaluation. The hourly energy generated in the second step is compared with the chronological hourly load using a Monte Carlo simulation technique

to obtain the desired adequacy indices. The overall simulation model is a concatenated chain of simulations that preserves the random nature of the concerned variables, their interaction and the chronology of the random events by mimicking the overall actual physical system.

3.2 Photo-voltaic Systems

The basic unit of a photovoltaic array is the PV cell, which absorbs photons of light from the incident solar radiation and releases electrons to provide a dc current to a closed electrical circuit. The amount of electric power generated depends on the physical construction of the PV cell, the operational constraints, and the atmospheric conditions, such as, the intensity of solar radiation on the cell surface, the ambient temperature around the PV module and the wind speed. The number of variables associated with a cell and with the atmospheric conditions that affect the energy availability increase the complexity in modeling PV systems.

3.2.1 Generation of Weather Data

The amount of solar intensity at a particular site dictates the power output from a PV system. Historical solar radiation data at the specified location is required in order to conduct relevant energy conversion analysis. Recorded irradiation data are not available for many locations around the world. Satisfactory evaluation of PV power generation for reliability purposes requires detailed hourly data. It is, therefore, necessary to generate synthetic hourly data for these studies.

A widely used computer program called WATGEN [37] has been used in the research to generate hourly weather data from the monthly mean values available at the particular location. The simulation program provides hourly synthetic data for global radiation,

ambient temperature, wind speed and ground reflectance ratio for a calendar year. The program fits into the first step of the overall simulation model of Figure 3.1 and has been linked to the second step program to enable a continuous simulation for a desired number of yearly samples.

The solar radiation before entering the earth's atmosphere has a value of 1367 W/m^2 , which is called the Solar Constant. As the solar rays enter the atmosphere, some are absorbed by ozone, carbon monoxide, dioxide and water particles. The amount of energy reaching the earth's surface depends on the Air Mass, which is the thickness of the atmosphere through which the rays have to travel. Air mass depends upon the time of day, season, altitude and latitude of the location. The solar intensity at the earth's surface also depends on the incident angle and weather conditions, such as, the cloud cover, wind and humidity. These complexities challenge the development of a mathematical model that can provide reliable results.

Stochastic simulation of hourly sequences using the global irradiation variable [38, 39] fails to recognize the optical characteristic of the atmosphere during the night (when there isn't any solar irradiation), therefore, losing the correlation required for accurate time series analysis. The time series model in WATGEN generates daily irradiation values by maintaining the correlation of the monthly variations [40]. The program uses the Clearness Index instead of the irradiation variable since the latter is dependent on the geography of the location. The clearness index, K_t , is the fraction of radiation that penetrates the earth's atmosphere. It can be calculated using Equation 3.1. The hourly clearness index values are obtained from stochastic disaggregation of the daily K_t values [41].

$$K_t = \frac{H_t}{H_0} \quad (3.1)$$

where, H_t = global irradiance on a horizontal surface
and H_0 = extraterrestrial irradiance on a horizontal surface.

3.2.2 PV Energy Evaluation

PV cells commercially produced for outdoor installations are made of crystalline silicon as the base material. Different layers of the materials are doped with desired impurities to form p-n junctions, which create an electric potential when exposed to light. The output of a PV module depends on many variables, such as, the solar irradiance, the angle of incidence, cell temperature, the operating point on the current-voltage characteristics, and other factors that affect the cell efficiency.

The amount of power that can be delivered by a PV cell is limited by its efficiency. The practical efficiency of commercially available cells is about 12-15% [12]. The efficiency depends on the ability of the cell material to respond to the incident light. Only a small fraction of the incident photon energy is capable of freeing electrons from their bonds, whereas, most of the energy is wasted by reflection, refraction or absorption that causes atomic vibrations to produce heat. Cell efficiency also degrades significantly as the operating temperature rises.

The power output from a PV cell can be estimated by studying a family of current and voltage (I-V) curves, as shown in Figure 3.2, the data for which is available from the manufacturer. The curve is the locus of the operating point of the PV cell. The area of the largest rectangle that can be fitted under the curve represents the maximum power that can be produced. The point where the edge of the rectangle touches the curve is the Maximum Power Point (MPP) of the cell. This is achieved when the impedance of the module array perfectly matches that of the load. The curve shifts vertically upwards (the output current increases) with increase in solar insolation and extends horizontally outwards (the voltage level increases) with a decrease in temperature.

PV systems are composed of modules, which contain a number of cells connected in series or parallel to obtain the desired voltage and current. The I-V curve for the module can be constructed by adding the I-V curves of the individual cells. The voltages along

constant current lines are added in a series connection and the current along constant voltage lines are added in a parallel connection of the cells. A module is rated in peak-watt (Wp), which is the maximum power it can produce at a radiation level of 1000 W/m^2 and at a temperature of 25°C .

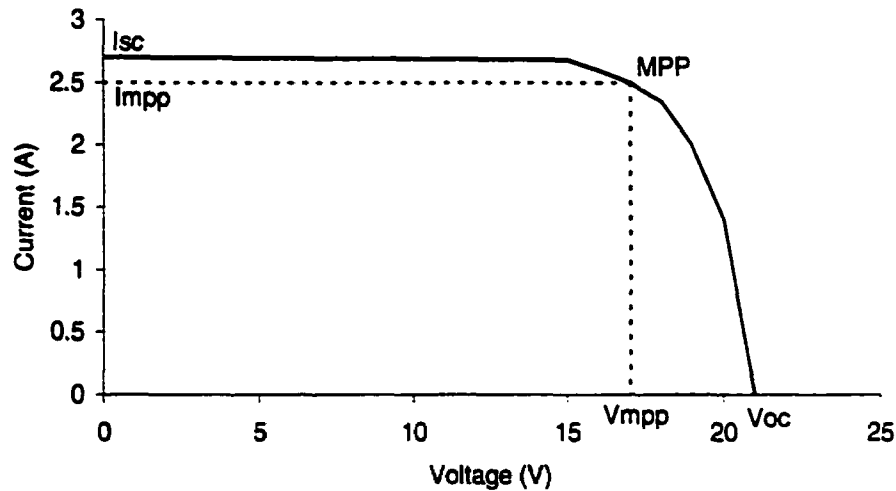


Figure 3.2: PV Cell I-V Characteristics

PV modules are assembled into arrays and are commonly mounted on fixed supports. Movable arrays with variable slope and azimuth angles for tracking the sun have not been considered in this thesis. The solar insolation on a surface is maximum when the beam is incident perpendicular to it. PV arrays are usually oriented due south and tilted at a slope equal to the latitude of the location to receive maximum energy.

A computer program called WATSUN-PV [42] simulates four types of PV systems: stand alone battery back-up system, PV/diesel hybrid system, PV water pumping system and utility grid-connected system. The software provides energy and economic analysis of these systems using a typical-meteorological-year hourly data and the necessary specification data for the array, inverter, battery, load, and other components in the

selected system. The underlying concepts in WATSUN-PV has been used to develop a program that fits into the second step of the overall simulation model illustrated in Figure 3.1. The program reads hourly weather data generated from Step 1 and produces hourly electrical power delivered by a PV system. The output of the program is fed into the adequacy evaluation model in Step 3 as a part of a continuous simulation that runs for a desired number of yearly samples.

The developed model decomposes the global radiation on the horizontal earth's surface into diffuse, beam, and reflected components and evaluates the total radiation incident on the tilted array surface. An I-V curve is constructed for the calculated insolation level and the temperature for the particular hour using the module ratings. The model includes a maximum power point tracker with the system and calculates the maximum power using the I-V curve. The calculated value is an initial estimate of the output power, which further affects the cell temperature. The new value of cell temperature is calculated as a function of the output power and heat losses from the panel surfaces. The I-V curve is adjusted for the new temperature value. An iterative calculation of output power and cell temperature finally provides a steady output power for that particular hour. The total power delivered is the sum of the power delivered by all the modules in the array.

3.3 Wind Energy Conversion Systems

The differences in temperature around the earth create differences in atmospheric pressure resulting in flow of air or wind. The amount of energy in the wind depends on its density and velocity. A wind turbine generator (WTG) can convert the kinetic energy in the wind into electrical energy. The amount of wind energy transferred to the rotating blades of the WTG depends on the density of the air, the rotor area, and the wind speed. The transfer of energy to the rotor produces a torque that drives an electric generator in the WTG. The electrical power generated depends on the availability of wind energy and the energy conversion characteristics of the WTG unit.

3.3.1 Generation of Wind Data

The electrical power supplied by a WTG is intermittent and varies randomly with time depending on the wind variation pattern at the system location. A reasonable evaluation of the power output from a WTG requires a large amount of reliable wind velocity data that describes the continuous variation of the wind with time. Hourly wind speed data have been collected for a number of years at many locations around the world. The wind data necessary for a wind system evaluation can be forecast using the available historical data for the specific site.

Wind is highly variable and depends on the geography and the atmospheric condition of the site. It has instantaneous, hourly, diurnal and seasonal variations. Wind speed near the earth's surface also depends on the terrain and obstacles. Besides chronological variability, wind has the characteristics of diffuseness and is not a concentrated source of energy. These factors must be recognized when estimating future wind variations for wind energy system studies.

Reliability evaluation of wind energy conversion systems using simulation techniques involves the generation of hourly wind speed data for a very large number of sample years. A time series model [43] has been used to generate synthetic data for any number of sample years. The simulated wind speed SW_t can be obtained from the mean wind speed μ_t and its standard deviation σ_t at time t using Equation [3.2]:

$$SW_t = \mu_t + \sigma_t * y_t \quad [3.2].$$

The data series y_t is used to establish the wind speed time series model in Equation [3.3]:

$$y_t = \phi_1 y_{t-1} + \phi_2 y_{t-2} + \dots + \phi_n y_{t-n} + \alpha_t - \theta_1 \alpha_{t-1} - \theta_2 \alpha_{t-2} - \dots - \theta_n \alpha_{t-n} \quad [3.3]$$

where $\phi_i(i=1,2,\dots,n)$ and $\theta_j(j=1,2,\dots,m)$ are the auto-regressive and moving average parameters of the model respectively.

The appropriate wind model should be selected to represent the wind characteristics at a particular site. A computer program developed to implement an ARMA(4,3) model [43] reads hourly data of mean wind speed and standard deviation for a year for the particular location and generates hourly wind speed data for any number of sample years. The time series model represents Step 1 of the overall simulation framework in Figure 3.1.

3.3.2 Wind Energy Evaluation

The amount of electrical power generated by a WTG depends on its design and on the wind velocity at the particular location. The wind speed determines the amount of wind energy available at the particular instant. The energy content of the wind varies with the cube of the average wind speed. The fraction of the available wind energy that can be utilized, however, depends on the design of the rotor blades, tower, generator and other components of the WTG.

The rotor area determines the amount of energy a wind turbine is able to harvest from the wind. The energy received by a WTG will vary with the square of the rotor diameter. The wind speed increases with the height above the ground level due to the reduced effect of surface roughness and obstacles. The height and structure design of the tower on which the WTG is mounted affects the wind speed received at the rotors. The type of generator and control systems used, the operating speed and many other variables in the WTG components affect the amount of electrical power that can be generated. The output power can be plotted against the average wind speed to construct a power curve for a WTG as shown in Figure 3.3.

Figure 3.3 shows that the power output of a WTG varies non-linearly with the wind speed. Wind turbines are usually designed to start running at wind speeds somewhere around 3 to 5 metres per second [15]. This is called the Cut-In Wind Speed, V_{ci} . A WTG will generate power as shown in Figure 3.2 as the wind speed increases from V_{ci} to the rated wind speed V_r . At the rated wind speed, the rated power P_r is produced. A wind turbine is controlled to stop at high wind speeds, typically above 25 metres per second [15], in order to avoid damaging the turbine. The maximum allowable wind speed is called the Cut-Out Wind Speed, V_{co} . The output power generated remains constant at the rated level P_r when the wind speed varies between V_r and V_{co} as shown in Figure 3.3.

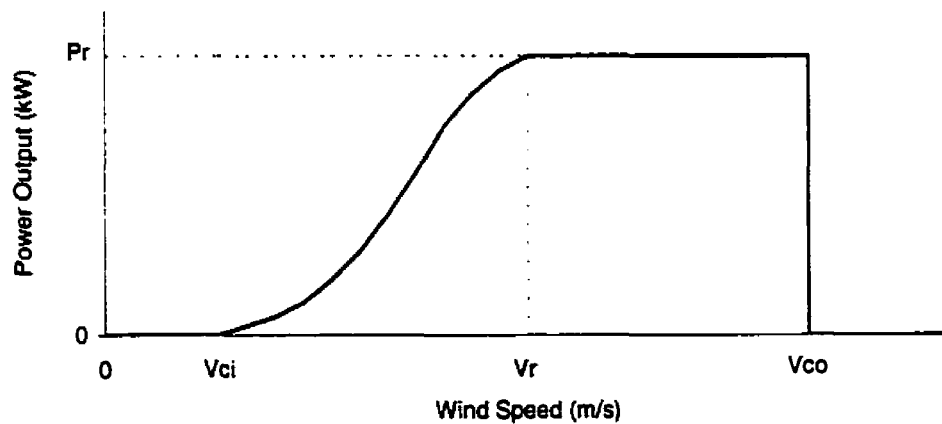


Figure 3.3: Power Curve of a WTG

The electrical power generated hourly can be calculated from the wind speed data using the power curve of the WTG. A computer program has been developed that reads the hourly wind data generated by the model in Step 1 of Figure 3.1, and calculates the power output every hour using the cut-in speed, cut-out speed, rated wind speed and the power rating of the WTG. The output of this program is fed into another program in Step 3 that conducts adequacy evaluation of the wind energy conversion system.

3.4 Adequacy Evaluation

The adequacy assessment of a power system containing renewable energy sources has been developed in three steps as illustrated in Figure 3.1. The necessary atmospheric condition data is generated for the system location in the first step. In the second step, the power delivered by the unconventional energy source is calculated, and depends on the weather data provided in the first step. The power generated in the second step is combined with the system load data in the final step to obtain various adequacy indices.

3.4.1 Composite SIPS Adequacy Model

The adequacy evaluation of composite SIPS that include PV and/or WTG is illustrated in this thesis. The overall generating system is divided into sub-systems of PV, WTG and diesel generators (DG). The modeling techniques described in the first two steps of Figure 3.1 are individually applied to the PV and WTG sub-systems in the composite SIPS. The output generated from PV and WTG sub-systems in the second step are combined with the DG sub-system to obtain the generation model for an overall system consisting of the three generation types. The evaluation in the third step of Figure 3.1 is conducted for the entire system in order to generate overall system reliability and cost indices. The adequacy evaluation model for a composite SIPS is shown in Figure 3.4.

The previous chapter notes that the reliability evaluation techniques used in conventional SIPS are largely deterministic and that these techniques cannot recognize the random behavior of the system. The number of random variables and the system complexities increase tremendously when PV and/or WTG units are added to SIPS. Reliability criteria based a fixed capacity reserve is not applicable since the capacity of a renewable source is not a deterministic value but a random function that varies continuously with the local atmospheric conditions and the interaction of these conditions with the unconventional

unit characteristics. Probabilistic approaches must be utilized to respond to these complexities and provide a realistic evaluation of composite SIPS.

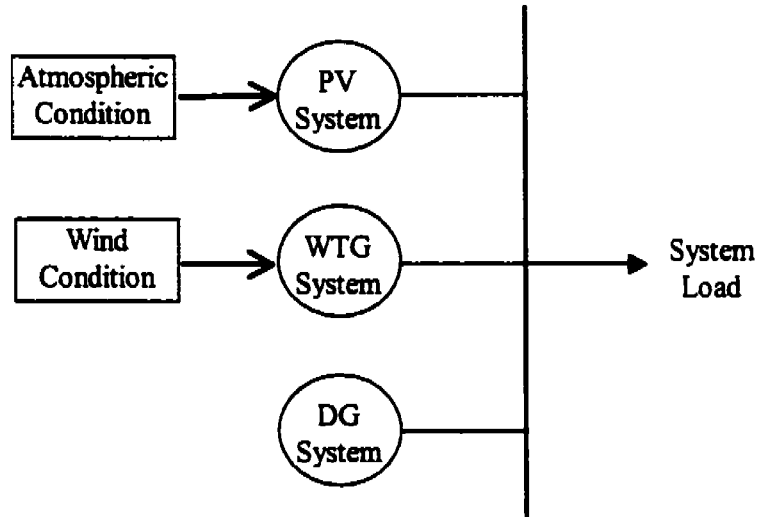


Figure 3.4: Composite SIPS Model

Conventional probabilistic risk indices can be applied to evaluate the risk in a composite SIPS. Risk indices, such as the LOLE and LOEE, are used in this research to measure the system risk in terms of load and energy curtailments. These techniques, however, have not been found applicable by SIPS planners and operators as discussed in the previous chapter. An abrupt change in the prevailing attitude to adequacy techniques cannot be expected even when renewable sources are added to create a major change in practical SIPS configurations.

The system well-being approach embeds the existing deterministic criterion in a probabilistic framework and should prove useful to SIPS operators and planners. The development of well-being techniques and the practical applications of these concepts to SIPS was the subject of previous research [7]. The developed methodologies have been

modified to incorporate the addition of PV arrays and/or WTG units in the conventional diesel systems and evaluate useful adequacy indices for composite SIPS.

Monte Carlo simulation has been applied to respond to the effects of the various random variables and their interactions that exist in a composite SIPS. The complexity in the system has been resolved by using a simulation model that mimics the atmospheric conditions and the corresponding system operation while recognizing the chronology of the actual events in the overall power systems. A Monte Carlo simulation technique has been developed for conventional SIPS [33] which can generate both conventional risk indices and well-being indices. The method has been modified in this research to include PV and wind energy sources that are energy limited, intermittent and erratic in nature. Additional energy based indices, and energy dispatch methods have also been implemented in the simulation model to carry out relevant studies on the cost and reliability of composite SIPS.

3.4.2 Simulating Composite SIPS

The adequacy evaluation of a composite SIPS using MCS is an extension of the method described in Reference [34] with modifications to include the effects of renewable energy sources. The continuous operation of the system is simulated for many years, moving successively from one event to the next as they occur under the influence of random variables of the system components and the surrounding atmosphere.

The random events considered in the simulation are the failures and repairs of the diesel units, PV arrays and WTG units; the hourly variation in the local wind speed, solar irradiation and ambient temperature; and the hourly variation in the system load. It is assumed that the atmospheric conditions and the system load vary hourly and remain constant throughout the hour. The failure and repair times are assumed to be exponentially distributed and can therefore be obtained using Equations (2.9 and 2.10).

The simulation task within each hour consists of creating the generation model and combining it with the load model to calculate and record the hourly capacity and duration values described in Section 2.5.2. The same task is repeated for the next hour maintaining the chronology of the recorded capacity and duration values. This process goes on, hour by hour, for a calendar year. The annual indices are calculated and recorded at the end of the year, and the simulation proceeds into the next year. The simulation process further continues, year after year, until the specified convergence criteria are satisfied.

3.4.2.1 Generation Model

The generation model is constructed by combining the outage history of all the generating units. The profile of the system operating capacity, and the capacity of the largest operating unit (CLUS) are recorded as shown in Figure 2.8. All the generating units are assumed to be in the up state at the start of the simulation. A random number between 0 and 1 is drawn for each unit to calculate its duration in the up state using Equation 2.9.

The operating state of each energy producing unit is identified for each simulated hour. If no failure or repair events occur during the hour, the capacity and the CLUS of each sub-system (PV, WTG and diesel sub-system) are calculated for the hour. The capacity and the CLUS of the diesel sub-system are calculated from all the diesel units that are in the up state. The capacity and the CLUS for the PV sub-system are calculated in three successive steps; generating the solar radiation, ambient temperature and wind speed data for that hour; calculating the output power from each PV array in that hour; and identifying all the arrays that are in the up state. A similar method is applied to the WTG sub-system. An operating constraint for system stability must be considered, as described later, when calculating the total capacity of the wind sub-system. The system capacity and CLUS for the hour is finally obtained from the capacity and CLUS of each sub-system.

If one or more units change state (fail or repair) during a simulated hour, the one-hour period is divided into a number of intervals that are separated at the instants when the changes occur. The capacity and the CLUS for the system are calculated as described above for each of these intervals. The final generation model is a profile of the system operating capacity and CLUS for a large number of years. The profile varies from one interval to the next, where each interval has a duration of one simulated hour or less.

3.4.2.2 Combining the Generation and Load Models

The next stage in the simulation is to combine the generation model with the load model. The load model is an annual chronological hourly load. The system load at each hour is compared with the total capacity to calculate the reserve margin. The load level is constant throughout the hour, whereas, the operating capacity can vary. The operating reserve at each interval within the hour is calculated and compared with the corresponding CLUS. The system state (healthy, marginal or at risk) during each interval is identified. It is observed whether a system state prevails or changes to another state when the simulation moves from one interval to the next within an hour, and from one hour to the next. The number of healthy, marginal and at risk states and their durations are recorded. The simulation proceeds for a large number of years using repeated annual load data and recoding the data necessary for system adequacy evaluation.

The generation model for the wind energy sub-system depends on the load model due to operating constraints imposed by system stability concerns. The power imbalance in supply and demand that are normally caused by load variations tend to accelerate or retard the rotating generators causing frequency and voltage fluctuations. Conventional units, such as diesel generators, respond to these stability problems by changing the supply power to match the demand through excitation and governor controls respectively. The WTG units, however, cannot provide the proper power balance since their power supply fluctuates randomly and at a higher rate relative to the load variations.

On the contrary, the rapid fluctuations in the WTG supply become the root cause for power imbalance instead of the load variations as in conventional systems. A common practice to solve this problem is to impose an operating constraint of limiting the wind system to only a specified fraction of the total demand. A 40% limit is a typical value in a composite SIPS [44].

A wind to diesel energy dispatch ratio has been used as an operating constraint to build the generation model for the wind sub-system. The simulation algorithm first compares the system load level with the PV sub-system capacity and dispatches all the available PV energy in that interval. The remaining load is then shared jointly by the wind and diesel systems in the specified ratio, always dispatching wind energy to allow a maximum of its share. In this way, the useful capacity of the WTG sub-system is calculated. The total operating capacity for that particular interval is the sum of the capacities of the PV, diesel and the useful capacity of the WTG sub-systems.

All the data that are required to calculate the system adequacy indices are recorded at each interval within an hour and at every hour within the calendar year. These data include the number of healthy, marginal and at risk states encountered, their individual durations, the total available energy in each sub-system, the energy supplied to the load and the energy deficiency at each interval. These values are summed at the end of each simulated year and a data bank of yearly sums is maintained to obtain the distribution of the annual indices.

3.4.2.3 Simulation Convergence

The simulation must be run for a large number of years for reasonable accuracy in the results. An appropriate time to stop the simulation must be determined using convergence techniques. The simulation program developed for composite SIPS implements a

stopping rule that involves observing the sample weight plot of the average value of the LOEE against the number of simulation samples.

The acceptable tolerance limits are specified for the convergence based on the knowledge of the system and the accuracy desired. The accepted deviation in the average LOEE, the number of successive years of acceptable deviation, the sum of the deviations in the span of the successive years, the maximum and the minimum number of simulated years are the criteria required for convergence in the simulation program.

At the end of each year, the deviation in the average LOEE from the previous year is calculated. When the percentage deviation is within the specified tolerance and this situation continues successively for the specified number of years, the program then checks for the sum of the deviations. The sum must also be within the specified limit for the simulation to be considered as converged. This criterion generally allows convergence when deviation occurs in both directions and avoids violation of convergence at a gradual rate. The minimum specified number of simulated years prevents premature convergence, whereas, the maximum number avoids excessive computation due to non-converging or poorly converging situations.

3.4.3 Composite SIPS Indices

The final results of the simulation program are the system adequacy indices calculated using the data recorded for the simulated years until convergence. The expected values of the indices and their distribution about the mean values are generated by the MCS model.

The conventional probabilistic risk indices are calculated using Equations (2.11 – 2.15) and the well-being indices are obtained from Equations (2.16 – 2.22). The distribution of an index is produced from its recorded annual values by plotting the number of

occurrences for different values of the index. The distribution provides additional information regarding the extreme situations and their likelihood.

The risk and health indices provide valuable information on composite SIPS adequacy. These indices can be used as useful indicators in various aspects of composite SIPS planning and operation studies. Additional energy based indices have also been developed to provide necessary information to incorporate renewable energy sources.

The Expected Energy Supplied (EES) by the PV or wind sub-system measures the amount of fuel offset by the PV and wind energy respectively. These indices are calculated by dispatching the available PV energy first and then calculating the wind energy consumed considering the operating constraints. Other useful indices are the Expected Surplus Energy (ESE) in the different sub-systems. These are the amount of energy that was available but could not be utilized. A high value of the expected surplus energy indicates an inefficient use of the generating sub-system. An index, designated as the Unused Energy Ratio (UER), is the ratio of the expected surplus energy to the expected energy supplied and can be calculated for a renewable energy sub-system using Equation 3.4:

$$\text{Unused Energy Ratio, UER} = \frac{\text{ESE}}{\text{EES}} \times 100\%. \quad (3.4).$$

The UER index provides useful information on deciding an appropriate level of PV or wind energy penetration in a composite SIPS. A low UER for a renewable energy system indicates a high demand for that energy source and suggests possible benefits of increasing the penetration level. There is a wide range of information that can be obtained from the basic and the additional system indices.

A composite SIPS evaluation tool named SIPSREL+ has been developed which implements the adequacy evaluation model shown in Figure 3.1. The software generates the mean values and the distribution of the adequacy indices discussed above.

3.5 Cost Evaluation

The expected cost benefit from offsetting costly diesel fuel is an important factor when considering the increased use of PV arrays and WTG units in SIPS. A realistic analysis of the cost benefits must also include the system reliability aspects. Any investment in conventional units or in renewable sources must be assessed not only in terms of fuel savings but also with respect to the resulting reliability level or the reliability worth to the customers.

There are different costs associated with the operation or expansion of a composite SIPS, all of which must be considered for an actual evaluation. The cost analysis in the thesis is mainly concerned with the fixed and variable costs that have significant effects on comparative studies of SIPS which operate under the influence of different system variables. The fixed costs mainly include the unit costs and the installation costs, and the variable costs include the fuel costs and the operation and maintenance costs. Customer interruption costs reflect reliability worth to the customers and should also be considered in cost evaluation of SIPS.

The utilization of PV and wind energy offsets diesel fuel in a composite SIPS. The amount of fuel saved by a renewable energy system can be calculated from its Expected Energy Supplied. The savings in monetary value depends on the price of the fuel and should also be compared with other associated costs. A present value analysis must be used when comparing the costs of operating the system over a range of years.

The evaluation of customer interruption cost requires a Composite Customer Damage Function (CCDF) for the system. The interruption costs at various outage durations are obtained through customer surveys for different consumer groups, which are then combined to create the system CCDF. The consumer groups considered in a composite SIPS usually consist of residential consumers, commercial consumers such as stores and government institutions such as schools. The CCDF is a non-linear plot of interruption cost per kW against outage duration. The CCDF for the IEEE-RTS [45] is shown in Figure 3.5.

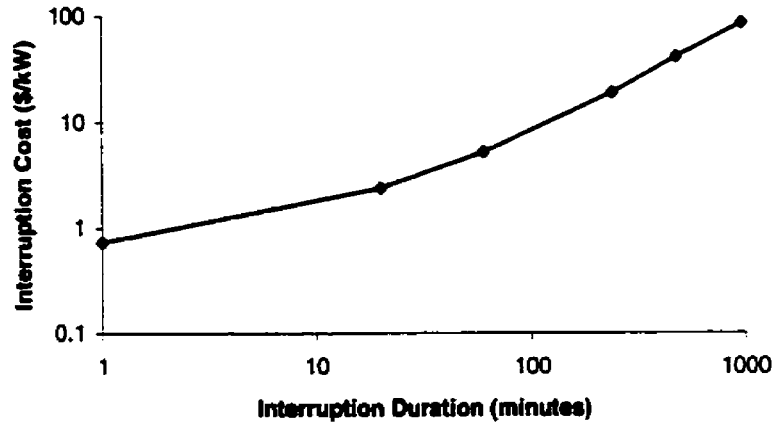


Figure 3.5: Composite Customer Damage Function for the IEEE-RTS

The simulation program calculates the duration and the energy curtailed at each interruption. The average load loss during the interruption is calculated by dividing the energy curtailed by the duration of outage. The interruption cost per kW for the outage is obtained from the system CCDF and multiplied by the load loss to get the customer interruption cost for the particular outage. The system interruption cost can be calculated using Equation (3.5):

$$\text{Customer Interruption Cost} = \sum_{i=1}^n c_i(r_i) \times l_i \quad (\$/\text{yr}) \quad (3.5)$$

where $c_i(r_i)$ = interruption cost in \$/kW for duration r_i
 r_i = duration in hours of interruption i
 l_i = load loss in kW of interruption i
 n = total number of interruptions.

3.6 Conclusion

The application of renewable energy generating sources, such as photovoltaics and wind energy conversion systems, is growing rapidly all over the world. The application of these sources to composite SIPS has been viewed as cost-effective alternatives to using the costly fuel required by conventional diesel generating units. The evaluation of the actual benefits requires appropriate system reliability and cost analysis.

A composite SIPS reliability evaluation model has been developed using Monte Carlo simulation. The overall system simulation incorporates renewable energy sources by linking three separate simulation models together. The objectives of the concatenated models are similar for both the PV and wind energy sources. The first simulation model generates synthetic data for each hourly atmospheric condition and the second model evaluates the hourly power output by the renewable energy sources. The third model combines all the conventional and non-conventional sources and simulates the overall system to obtain the desired reliability and cost indices.

Comprehensive adequacy assessment of composite SIPS which involve the utilization of highly variable renewable energy sources that depend on a large number of random variables can be performed using probabilistic techniques. Existing deterministic criteria can be embedded in a probabilistic approach using well-being analysis. The well-being

indices generated by the simulation model should prove useful in the evaluation of composite SIPS.

A wide range of indices for adequacy and cost evaluation can be generated by the computer program developed to implement the simulation model. Conventional risk indices can provide useful information in composite SIPS planning. Additional energy based indices have also been developed to help system planners examine better utilization of renewable sources considering energy dispatch priorities and constraints related to system stability.

A composite SIPS evaluation model that can recognize the inherent system complexities has been developed and implemented in a software package designated as SIPSREL+. This software tool can be used to conduct various studies related to system adequacy and cost in order to analyze the actual benefits obtained from renewable energy sources in a composite SIPS.

4. COMPOSITE SMALL ISOLATED POWER SYSTEM EVALUATION TOOL

4.1 Introduction

The methodologies developed for the reliability and cost evaluation of a composite SIPS have been implemented in a graphical user-interface software tool designated as SIPSREL+. The tool can be used to generate appropriate system indices to analyze conventional diesel systems that include PV and wind energy generating sources.

The software tool is a stand-alone PC application that requires a Windows 3.1 or later operating system. The hardware requirements are a minimum of 80486 microprocessor, 4 MB of memory, 4 MB of disk space and a Windows compatible display. A computer with high processor and bus speeds is recommended since the simulation programs take considerable computation time.

The software has been developed as an educational tool using an object oriented approach. This approach facilitates the analysis, design and development of a software product in a cyclic process with incremental development and modification in each cycle. The tool has been developed in multiple phases in parallel with the advancement of the research work. The software product at the end of a particular phase was used to provide results for further research work, and new developments in the research were implemented by modifying the software in the next phase in a continuous cycle. Considerable effort is required when testing a software product that includes multiple functions and a number of concatenated mathematical models. The use of object oriented concept facilitated the testing process by applying an incremental approach which started

with a simple product. The analysis, design and development of the initial phase of the software are described in Appendix A.

The initial phase began with an energy system supplied only by PV arrays. The next phase included more complexities in the PV system by considering the failure and repair events. The subsequent phases added diesel units, WTG units and more complexities in the system, one step at a time, using incremental development in a continuous loop process. The software tool, thus developed, is expected to be reused and extended periodically with minimum effort for future research work in this area.

The software tool runs from a graphical user-interface (GUI) that assists the user to select desired options, provide proper data and display results in an uncomplicated manner. The GUI has been developed in Visual Basic. The source codes for the engine application are written in C++ and FORTRAN programming languages. The GUI presentation layer is loosely coupled to the engine application layer and can, therefore, be easily replaced by a modified or a newly designed user-interface program.

The procedure involved in using the software tool to conduct different types of evaluation is described in the User's Manual provided in Appendix B. Figure 4.1 shows the initial display produced by the tool when it is activated.

4.2 Scope of the Evaluation Tool

The software tool can be used to evaluate a small power system that is supplied by diesel units, PV arrays, WTG units or any combination of these energy sources. The tool integrates different evaluation models described in the previous chapter. The selected system requires necessary input data and is simulated for a large number of years until the specified convergence criteria are met. The final results are a display of the system adequacy, energy and cost related indices.



Figure 4.1: Initial Display from the tool SIPSREL+

4.2.1 Integration of the Developed Models

SIPSREL+ has been developed as an integrated framework that incorporates the various methodologies developed for reliability and energy assessment of composite SIPS. An overall evaluation of different system compositions of composite SIPS can be performed from a common platform. Figure 4.2 illustrates the integration of different models that have been implemented in the software tool.

A separate computer program has been developed for each model shown in Figure 4.2. The models are linked together into an overall simulation program using the MCS

approach. Each of the model programs can be easily replaced by a new one when modification of the evaluation tool is required for future research.

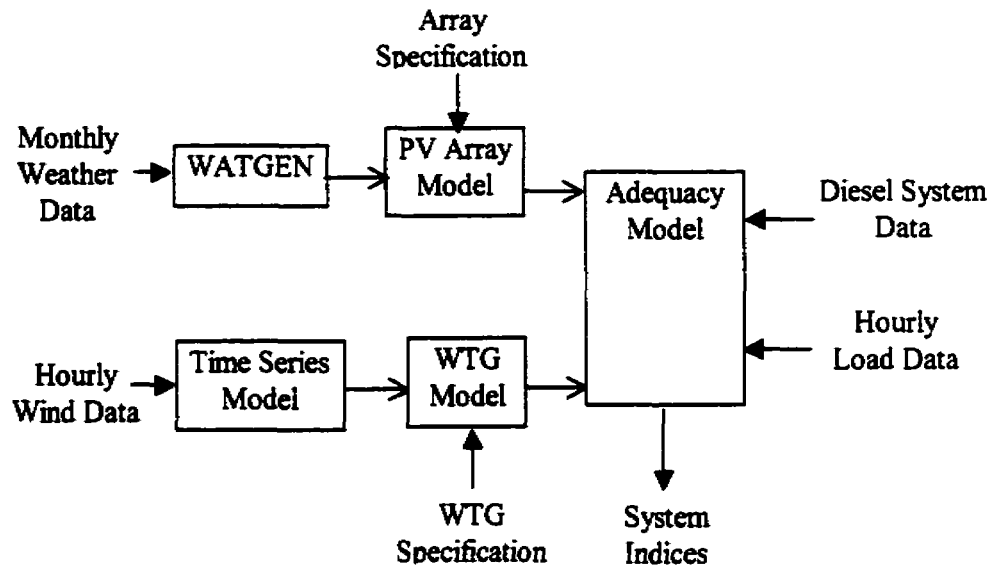


Figure 4.2: Integrated Framework of the Evaluation Tool

The different models that are integrated in the software tool interact with each other to perform a sequential simulation of the entire system for a large number of years. The basic algorithm used in the overall simulation of a composite SIPS is illustrated in Figure 4.3.

4.2.2 Input Data Requirement

The necessary input data required to run the programs in SIPSREL+ are either entered directly into the user-interface forms that are linked to the tool database or provided as separate data files that contain larger volumes of related data. The user-interface program provides a number of data forms sequentially prompting the user to type in the proper

input data. The forms are displayed with default data values that can be changed by the user. A collection of data files is available in the tool library with the type of data that must be provided in files. The proper data files can be selected from the lists displayed by the program. Any changes made to the contents of the selected file from the user-interface do not alter the original files in the library. The program saves the changes in a copy of the library file and the data in the duplicate files are used by the engine application.

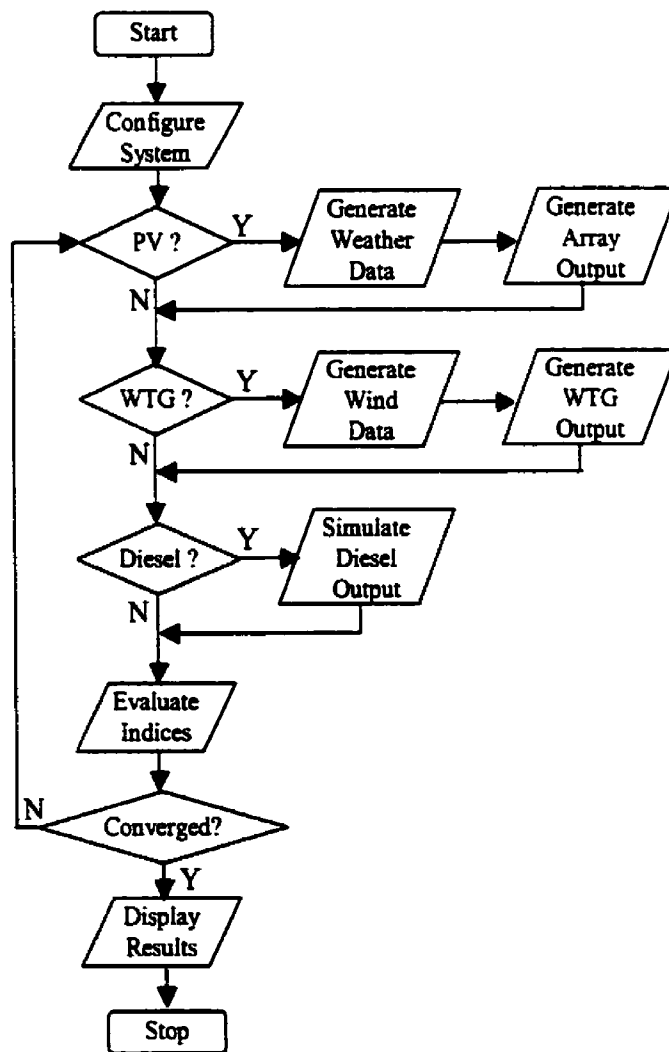


Figure 4.3: Program Algorithm

The user must select the type and the number of the energy generating sources to configure the desired power system in the program. The selection is made by checking the appropriate boxes in the user-interface window shown in Figure 4.4. The operating constraint in terms of wind to diesel dispatch ratio must also be specified if the system contains both diesel and wind generating units. The default value of “-1” indicates that no operating constraint is considered.

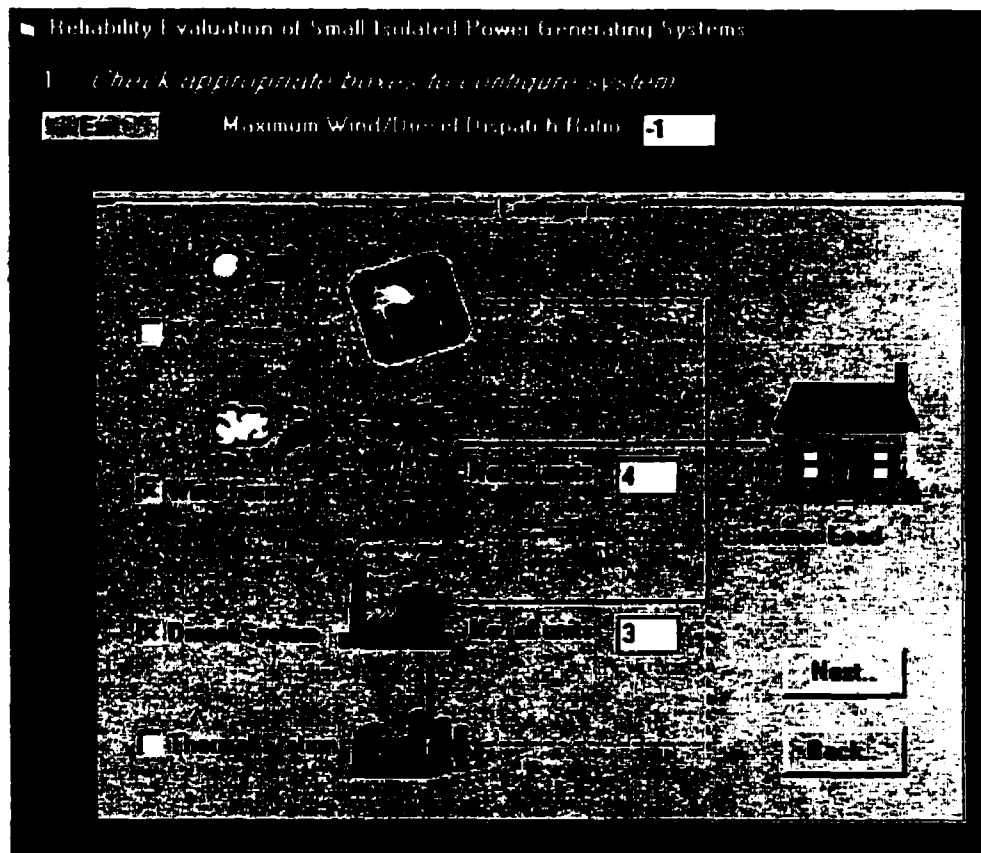


Figure 4.4: System Selection Window

The monthly mean global solar radiation, wind speed and ambient temperature data and the PV array specification data that are required for a PV system are provided in data files respectively. The appropriate files can be selected in the GUI to display their

contents and to modify them if desired. The database interface for the weather data required for a PV system is shown in Figure 4.5.

Select Data File:

Monthly Average Weather Data:

	Jan	Feb	Mar	Apr	May
Wind Speed (m/s)	24	23	22	22	22
Temperature (deg)	13	9.6	10	13.2	18.8
Radiation (kJ/m ²)	6.95	8.58	13.55	18.05	21.2

Change Data:

Temperature (deg)
Apr

Site Latitude:

Figure 4.5: Weather Data Interface for a PV System

The hourly mean wind speed and the standard deviation data required for the wind system analysis are available in a library of data files collected for different geographical locations. The appropriate files for a particular system location must be selected from a list of the available files. The WTG specification data are directly entered into the GUI form. The user must also provide the generating unit capacities and their MTTF and MTTR data.

The program also requires the system peak load data and the customer interruption cost related data to be entered by the user. The hourly chronological load curve data in per unit of the peak load, and the CCDF data are provided in data files which can be selected and displayed in the user-interface as shown in Figure 4.6.

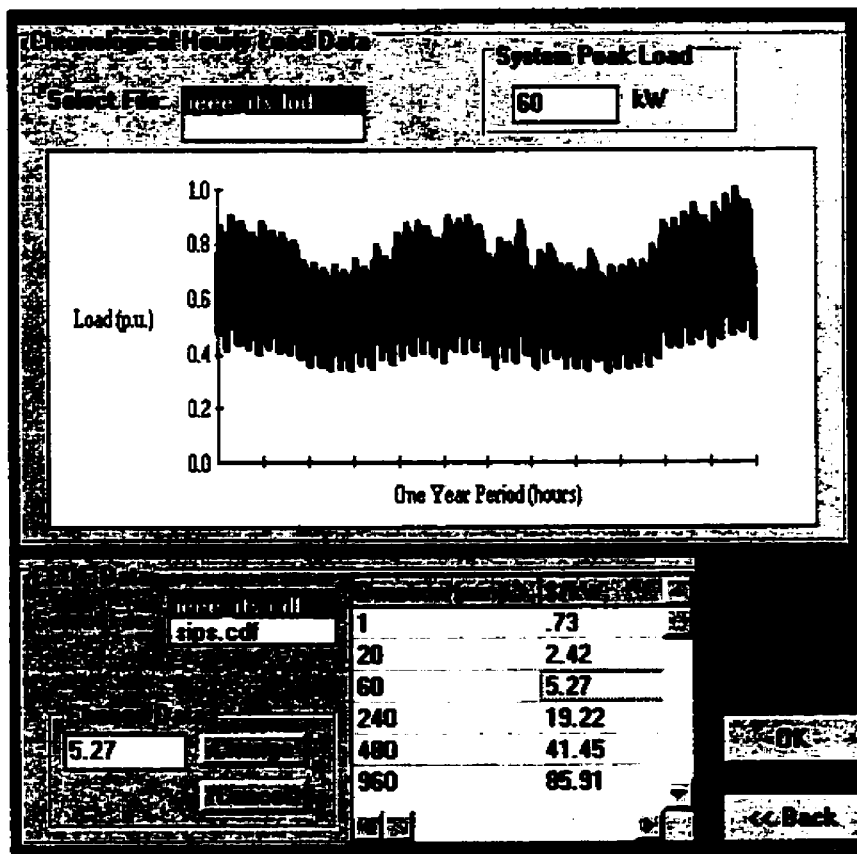


Figure 4.6: CCDF and Load Data Interface Window

The user must also provide the convergence data before the simulation program can be run. The acceptable deviation in the system average LOEE, the minimum number of consecutive years of acceptable deviation, the maximum and the minimum number of simulation years and the random number generator seed must be entered in the appropriate interface window.

The simulation program for the selected system can only be run when all the necessary data have been provided as prompted by the GUI program. The simulation begins when the user clicks the appropriate button. The program runs for a significant amount of time

depending on the speed of the computer, the criteria selected for convergence and the configuration of the selected power system.

4.2.3 Output Results

The simulation program in SIPSREL+ is terminated when the specified convergence criteria have been met. The output results are the conventional risk indices, well-being indices and additional energy based indices that have been developed to analyze the performance of renewable energy sources.

The conventional risk indices generated are the LOLE, LOEE, Expected Interruption Duration (EINTDUR), Expected Energy Not Supplied per Interruption and the Frequency of Interruptions. The Healthy State Probability, Marginal State Probability, Loss of Load Probability (LOLP), Loss of Health Expectation (LOHE), Expected Health Duration (EHDUR), Expected Margin Duration (EMDUR) and the Frequency of Marginal States are the system well-being indices that are included in the results. The index Interrupted Energy Assessment Rate (IEAR) is also produced which when multiplied by the LOEE gives the Customer Interruption Cost for the system.

The energy based indices generated by the simulation program are the Expected Energy Supplied (EES) by the PV, WTG and diesel sub-systems in the composite SIPS under evaluation. These energy values can be converted into litres of diesel fuel using the heat rate of the diesel generators. The fuel cost for the diesel units and the cost of fuel saving in the renewable sources can then be calculated using the price of diesel at the system location.

Additional indices produced for the renewable energy systems are the Expected Surplus Energy (ESE) and the Unused Energy Ratio (UER). The significance of these indices has already been described in Section 3.4.3.

The software tool also generates the distributions of the output indices about their mean values. The distribution can be displayed in a graphical form as illustrated in Figure 4.7.

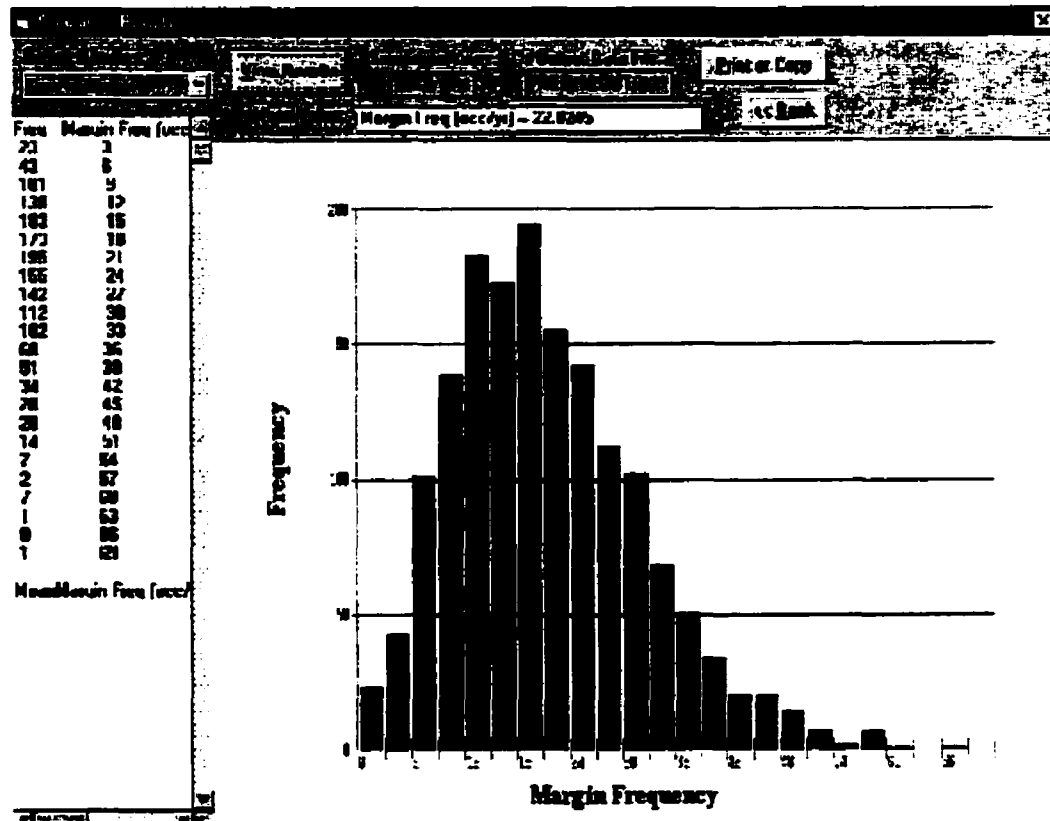


Figure 4.7: Distribution of an Index

4.2.4 Limitations of the Tool

The software tool SIPSREL+ has been developed for the evaluation of small isolated power systems that contain photovoltaic and wind energy sources. The tool can also be applied to conventional systems or to larger systems for conducting generating capacity adequacy studies. The methodology implemented and the indices generated are, however, more useful for the analysis of composite SIPS.

The simulation program used in SIPSREL+ requires detailed data on generating unit performance and load variations in order to simulate hourly events. The availability of such data for many remote isolated systems is not common. It is also important to have reliable weather data for the system location in order to have realistic and usable indices.

The computation time required for the simulation process is quite significant when PV arrays or WTG units are included in the system. Table 4.1 illustrates the time taken to run the program for 100 simulation years on a PC with a 500 MHz Pentium III microprocessor (166 MHz bus speed). The results are for a typical composite SIPS and will differ for different system sizes and configurations.

Table 4.1: Computation Time Requirement

System Configuration	Computation Time for 100 years
Only Diesel Units	2 seconds
Diesel and WTG Units	20 seconds
Diesel and PV Units	4 minutes 18 seconds
Diesel, WTG and PV Units	4 minutes 32 seconds

The accuracy in the results increases with the number of yearly samples taken. There is, however, a limitation in the level of accuracy that can be obtained by the simulation method. The selection of a different random number seed can provide slightly different results. The user should aim for reasonable and achievable accuracy. Discussion on levels of accuracy and the methods to achieve them are provided in Section 4.4.

Some of the assumptions made in the program are that all the generating units are in service at all times except when on outage due to failure. Scheduled maintenance of the generating units is not considered. The generating units can reside in only two states, either operating or failed, and the failure and repair events are assumed to be independent. The weather data are generated for a large number of years with a different

set of data every year, whereas, the same annual load data is repeated each year. The existing deterministic criteria can be different in different systems. The developed tool only considers the LLU as the accepted deterministic evaluation criterion while evaluating the system well-being indices.

4.3 Application to the IEEE-RTS

The application of the software tool is illustrated by using it to evaluate the system adequacy effects of including PV and wind energy sources to the IEEE-RTS [45]. The IEEE-RTS has 32 conventional generating units with a total capacity of 3405 MW. The system load is 2850 MW. PV arrays and WTG units are added to the system at penetration levels of 1% and 5% respectively of the total capacity. The system is simulated using SIPSREL+ and the generated indices are studied to analyze the system. The system data that is required and the results that are obtained are described in the following sub-sections.

4.3.1 System Data

The initial task in applying SIPSREL+ to the renewable energy injected IEEE-RTS is to configure the desired system by selecting the PV, wind and the diesel systems together in the “System Selection Window” shown in Figure 4.4. A maximum wind to diesel dispatch ratio of 0.67 was chosen to limit the wind energy to supply not more than 40% of the energy demand at any time for stability concerns.

The weather conditions used in the study are those determined for the Swift Current area. The monthly mean data for global radiation, wind speed and ambient temperature are available in a file named “SWIFTCT.WTH” in the data library. The contents of the file are provided to the software tool as input data for the PV system. The hourly mean wind

speed and the standard deviation data for Swift Current location are available in the files “SWIFTCT.WMN” and “SWIFTCT.WSD” respectively and are provided as the necessary input data to the wind system. The contents of all of these files are shown in Appendix C.

The PV system added to the IEEE-RTS has 750 arrays of Nukem PS94T, 94 Wp modules [42] with a total capacity of 35.25 MWp. Each array consists of 50 groups of 10 series modules. The module specification data is available in the data file “PS94T.ARR” and is shown in Appendix C. The wind farm consists of 100 WTG units, each with a capacity of 1650 kW, totaling to 165 MW capacity. The cut-in, rated and cut-out wind speeds for the WTG are 14.4, 61.2 and 90 Km/h respectively. These data are entered directly in the data entry form provided by the tool. The PV arrays have a 2% FOR, with a MTTF and MTTR of 4380 and 90 hours respectively. The WTG units have a 4% FOR, with a MTTF and MTTR of 1920 and 80 hours respectively. The generation data for the conventional units in the IEEE-RTS are also given in Appendix C. These data are entered into the appropriate data entry forms in the user interface of the software tool.

The system peak load of 2850 MW is entered into the program. The chronological hourly load curve for the IEEE-RTS is available in the file “IEEE_RTS.LOD” which is selected as the input file for the tool as shown in Figure 4.6. The load curve data in per unit of the peak load is shown in Appendix C.

The evaluation of the indices related to customer interruption costs requires CCDF data. The CCDF for the IEEE-RTS is shown in Figure 3.5 and the corresponding data are available in the file “IEEE_RTS.CDF”. The file is selected as the input data file in the interface window shown in Figure 4.6.

The simulation convergence data must be entered in the simulation data form displayed by SIPSREL+. The criteria defined for convergence are a deviation within 0.25% of the

average LOEE, at least 25 years of consecutive acceptable deviations, a maximum of 5000 years and a minimum of 3000 years of simulation.

The simulation can be run after providing all the necessary input data. The program in this case was terminated after 3020 years of simulation with the specified convergence criteria.

4.3.2 Description of the Results

The adequacy effects of injecting PV and wind energy sources to the IEEE-RTS can be studied by analyzing the indices that have been generated after the termination of the simulation program in SIPSREL+. The system risk and well-being indices are shown in Table 4.2 and the energy indices in Table 4.3. The indices for the IEEE-RTS without any renewable energy penetration are also listed in the tables for comparison under the heading Base IEEE-RTS.

Table 4.2: System Risk and Well-being Indices

System Index	IEEE-RTS with Renewable Energy	Base IEEE-RTS
LOEE (MWh/yr)	807.4020	1075.6100
LOLE (h/yr)	6.8714	8.7904
LOHE (h/yr)	94.6694	114.6470
Healthy State Probability	0.989163	0.986877
Marginal State Probability	0.010050	0.012117
LOLP	0.000787	0.001006
EHDUR (h)	477.0990	425.9350
EMDUR (h)	4.4493	4.7871
EINTDUR (h)	4.1495	4.5943
Frequency of Margin	19.7331	22.1127
Frequency of Interruption	1.6560	1.9133

Table 4.3: Energy-based System Indices

System Index	IEEE-RTS with Renewable Energy	Base IEEE-RTS
EENS/INT (MWh)	487.5730	562.1680
IEAR (\$/kWh)	5.1857	5.1966
PV EES (MWh/yr)	50554	-
WTG EES (MWh/yr)	239944	-
DG EES (MWh/yr)	15005800	15296000
PV ESE (MWh/yr)	0	-
WTG ESE (MWh/yr)	0	-
DG ESE (MWh/yr)	12918500	12637500
PV UER (%)	0	-
WTG UER (%)	0	-

4.4 Simulation Convergence and Limitations

The accuracy in the simulation results increases with the number of simulation samples. The more samples, the longer the simulation time. Another concern is that a different starting seed can yield different results. It is, therefore, desirable to know the accuracy limitations in the results when a starting seed is chosen at random. Several comparative studies have been done using different seeds and different system sizes with different renewable energy penetrations and different levels of reliability to obtain suitable convergence criteria and achievable accuracy.

The simulation convergence pattern for the IEEE-RTS is compared with two small identical capacity systems with different load levels. The SIPS considered have two 40 kW and one 70 kW diesel generating units with 5% FOR. The IEEE-RTS chronological hourly load curve is assumed for all three systems. SIPS 1 has a peak load of 20 kW and has a higher system reliability compared to SIPS 2 which has a peak load of 73 kW. The convergence patterns for the three systems are compared in Figure 4.8.

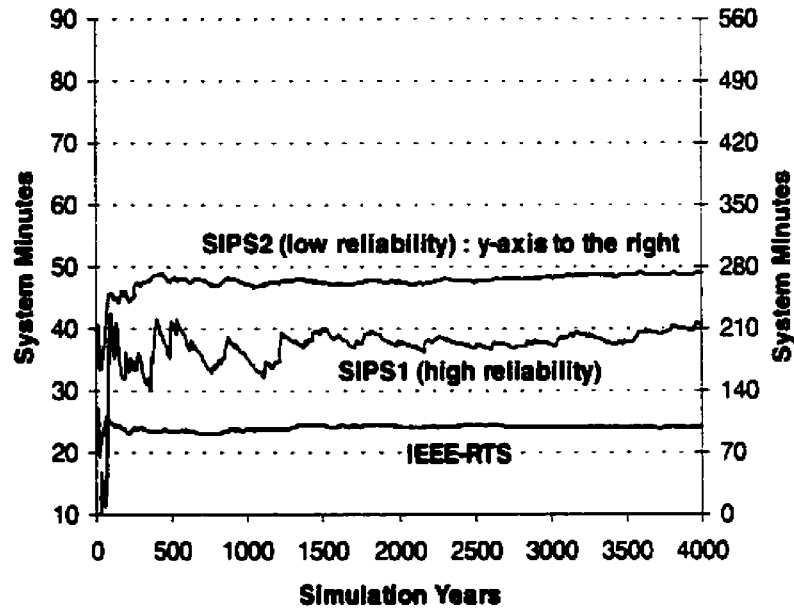


Figure 4.8: Convergence Patterns Comparison

The convergence criteria are based on the LOEE index for the reasons discussed in Section 2.5.3. The LOEE index cannot, however, be used to compare reliability in systems of different size since larger systems will have a higher LOEE regardless of the reliability level. The System Minutes (SM), has therefore been used in Figure 4.8 to compare the three systems.

It can be seen from Figure 4.8 that the IEEE-RTS converges much better than SIPS 1. The SIPS 2 is similar to SIPS 1 but has a lower reliability. The convergence pattern of SIPS 2 is better than that of SIPS1. It has been observed that smaller systems with a few number of generating units require more simulation samples to satisfy a specified set of convergence criteria compared to larger systems. The computation time per simulation sample is, however, much lower for a small system. Convergence is achieved more quickly in systems with lower reliability.

The simulation convergence also depends on the types and the penetration levels of the renewable energy sources injected in the system. The convergence profiles for two sets of system simulations are illustrated in Figure 4.9. Each set consists of three system configurations; a system with only conventional units, the system including PV arrays, and the system including WTG units. The three configurations were maintained at the same LOLE level by varying the peak loads so that the effect of renewable energy penetration on the convergence can be studied. The lower set in Figure 4.9 includes the IEEE-RTS, the IEEE-RTS with 1% PV penetration, and the IEEE-RTS with 5% wind energy injection. The upper set includes SIPS 2, SIPS 2 with PV and SIPS 2 with wind energy penetration of 27% of the original system capacity. The LOLE of the three systems in the upper set is 26 h/yr.

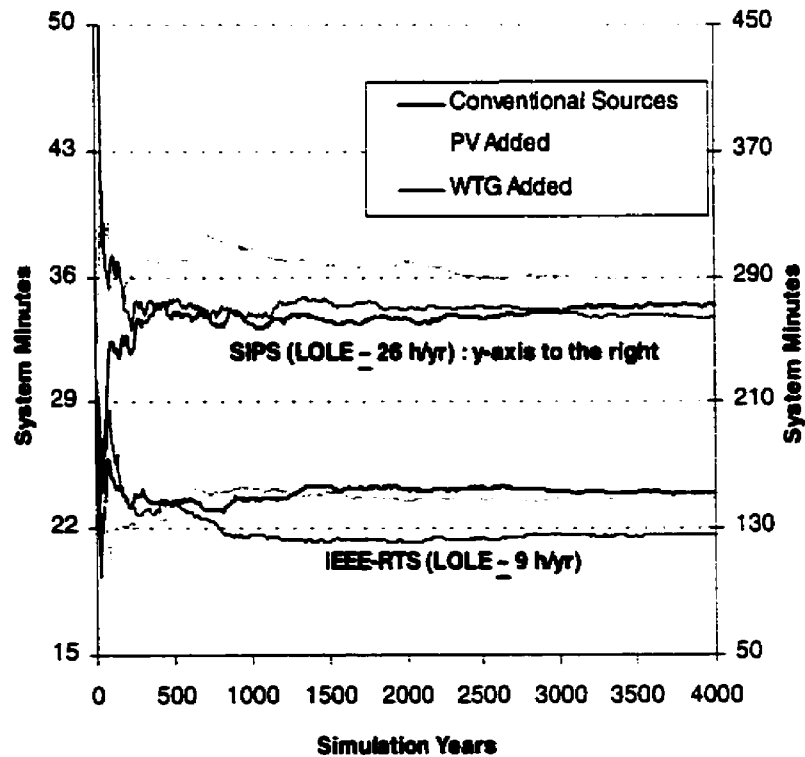


Figure 4.9: Effect of Renewable Energy Injection on Convergence

It can be observed from Figure 4.9 that the simulation takes a longer time to settle to a steady level when PV arrays or WTG units are included in a system. The reluctance to converge becomes more profound with higher renewable energy penetration levels. It has also been observed that wind energy systems converge better than PV systems.

The information shown in Figure 4.9 illustrating the convergence profiles of the different systems is not sufficient to draw any general conclusions on the necessary length of simulation and the accuracy that can be obtained. This is because the convergence of a simulation process strongly depends on the starting seed chosen to generate the random numbers. The curves illustrated in Figures 4.8 - 4.9 have been generated from one particular seed. The selection of a good seed will drive the simulation to converge quickly, whereas, a bad seed can lead to non-convergence or poorly converging situations.

When a selected system is simulated using different random number seeds, the random fluctuations in the profiles generated will eventually stabilize at different levels. The seeds that drive the simulation to convergence at the correct steady level are the desirable seeds. The ideal seed for a particular system is one that drives the simulation to converge quickly and to produce the correct results. A quick convergence is not desired if the results generated are not close to the correct values. The simulation results can be compared with standard analytical results for conventional systems. However, alternative reliable methods are not available to compare the results for systems containing PV or wind energy sources. A major problem in these studies is that there is no way of determining whether the results generated by the simulation process are correct or within acceptable limits. The accuracy of the results must, however, be known in order to decide when to stop the simulation program.

One way to determine the correct results is to repeat the simulation using a large number of seeds and to take the mean of all the different results. When the convergence curves generated by the different seeds are traced on a graph, the bad seeds can easily be

identified and discarded. Figure 4.10 illustrates the convergence profiles using 10 different random seeds on the SIPS considered in Figure 4.9 with 27% PV penetration. The peak load has been taken as 53 kW in this case. The system LOLE is 9 h/yr. The profile of the mean LOEE value is shown by a dark line.

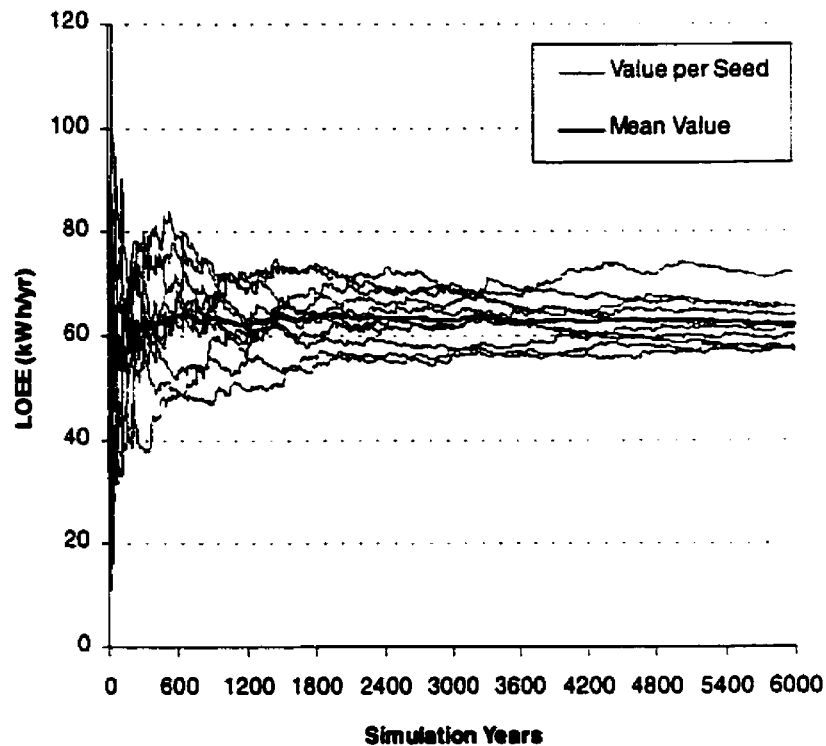


Figure 4.10: Convergence with Different Seeds

It has been noted above that small systems with high reliability and large PV penetration have great difficulty in achieving simulation convergence. The system considered in Figure 4.10 is a good example. The fluctuations in the curves can be seen to settle within a narrow band after about 4000 years of simulation. It is desirable to run the simulation until the width of the convergence band reaches a minimum level under these conditions. The accuracy achieved by a random seed will be the best for that situation.

Figure 4.10 illustrates that the convergence profile generated by a random seed can deviate widely from the mean value. The deviation reduces as the simulation approaches convergence and deviations for the different seeds are different. The deviation expected from a random seed can be estimated by plotting the absolute deviation from the mean for a large number of random seeds. The absolute deviations cannot be compared for different systems since a system with a high mean value will have higher absolute deviation relative to a system with a low mean value. The absolute deviation for a system can be normalized by the corresponding mean value for comparative studies. Figure 4.11 illustrates the absolute deviations in percent of the mean values using 10 different seeds. The three systems each contain two 40 kW and one 70 kW diesel units with FOR of 5%. In the renewable energy cases, 27% WTG and 27% PV were added respectively. In the basic diesel configuration, the load was reduced to maintain the same LOLE of 9 h/yr. This was also done in the renewable energy cases.

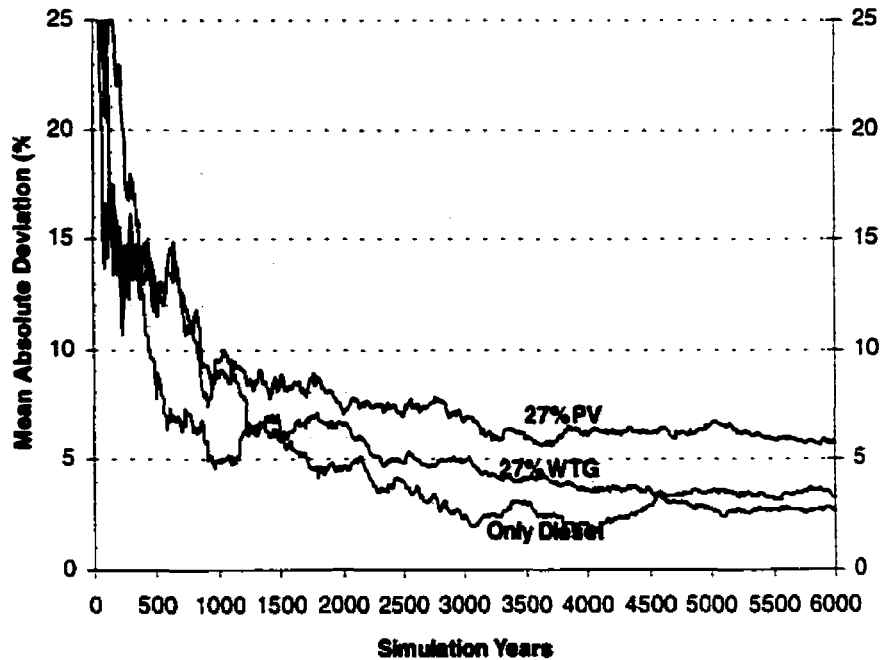


Figure 4.11: Percent Absolute Deviation for 10 Seeds

Figure 4.12 shows similar plots to those in Figure 4.11 for systems of different size, renewable energy penetrations and reliability levels. The systems compared include the six systems shown in Figure 4.8 and the three systems shown in Figure 4.11. It can be observed from Figure 4.12 that accuracies within a 3% deviation can be obtained for most systems when the simulation is forced to run for at least 4000 simulation years. A minimum of 4000 simulation years has therefore been taken as a convergence criterion in the studies described in the thesis. The accuracy is lower for small systems with relatively high reliability levels and PV array penetrations. The top curve in Figure 4.12 is for the system in Figure 4.10 and has a deviation of about 6% after 4000 simulation years. The accuracy for such systems can be unacceptable if reliance is placed on only one seed. The averages obtained from two different seeds have been used.

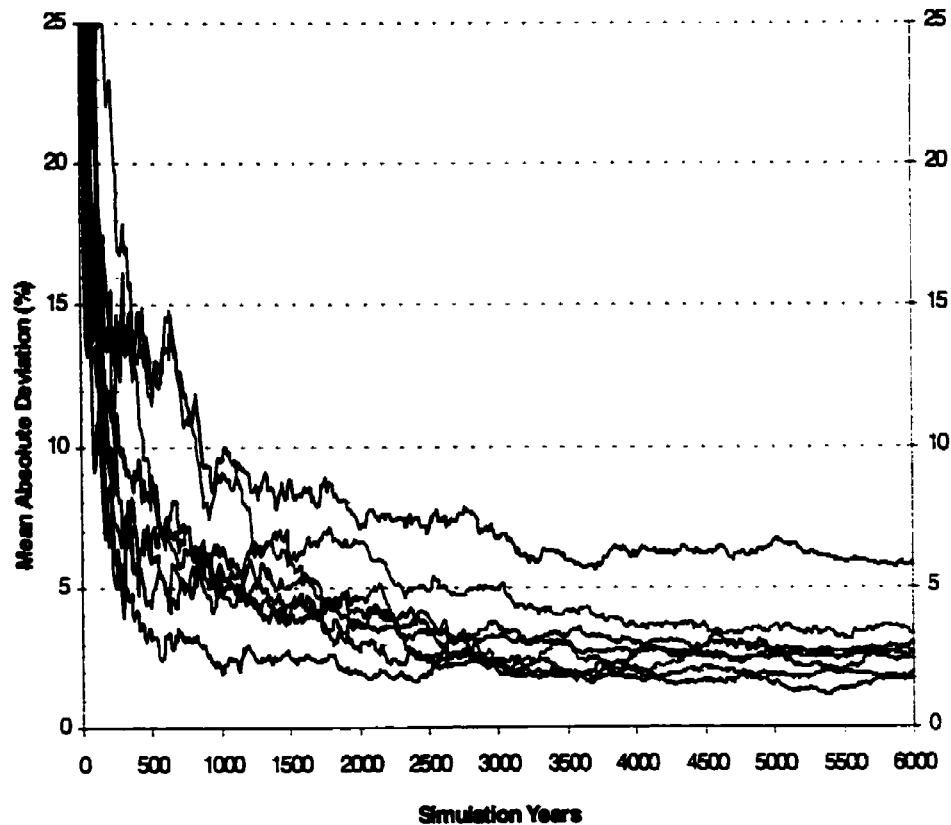


Figure 4.12: Comparing Absolute Deviations for Different Systems

4.5 Conclusion

The methodologies developed for the analysis of composite SIPS consist of a number of mathematical models designed to conduct different functions within the evaluation process. The different models have been linked together in an integrated framework and implemented in a software tool named SIPSREL+.

SIPSREL+ has been developed as an educational software with the objectives of providing an easy-to-use tool which can incorporate anticipated changes with ease. An object-oriented concept has been applied in the development of the software with provisions for reuse and future modifications. The tool is equipped with a GUI that interacts with the user to receive necessary data and to display useful information and results.

The software tool uses MCS to simulate composite SIPS with a wide range of configurations. The sequential system simulation concatenates individual programs for synthetic weather data generation, PV array modeling, WTG modeling and adequacy evaluation. The input data for the site atmospheric conditions, PV and WTG specifications, diesel unit data, load variations and convergence criteria are required for the simulation program. The data are either provided in files or entered directly into the GUI forms. The results obtained include conventional risk indices, well-being indices and energy based indices. The application of SIPSREL+ has been demonstrated by using it to evaluate the adequacy of the IEEE-RTS system when PV and wind energy sources are included.

The simulation length required when SIPSREL+ is used for a particular system and the level of accuracy that can be achieved has been studied. A system simulation is a time consuming process that should be stopped when it reaches convergence. The convergence criteria must produce results with acceptable accuracy. The convergence of

the simulation process requires more samples for small systems with high reliability and high renewable energy penetration.

The accuracy of the results when a random seed is used in the evaluation cannot be known since the correct values are unknown. Studies on a number of different systems using various seeds show that accuracy can be achieved within 3% deviation from the mean results in most cases when a simulation is run for at least 4000 years. The inaccuracy is much higher (within 6% deviation from the mean) for small systems with high PV penetration and relatively high reliability. These types of systems should be evaluated using the mean indices from two simulation runs with different seeds. The studies described in this chapter help the user to estimate the level of accuracy and obtain a better appreciation of the results that can be obtained from SIPSREL+.

5. EFFECTS OF SYSTEM PARAMETERS ON COST AND RELIABILITY

5.1 Introduction

The developed evaluation tool has been used to carry out a wide range of reliability and cost analyses of various types of SIPS including different combinations of conventional and unconventional energy sources. The effects of different parameters that characterize SIPS have been studied by comparing the system indices produced by the software tool.

The effects of different factors on system reliability have been compared using both the conventional risk indices and the well-being indices. Customer interruption cost comparisons have also been considered in analyzing relative adequacy levels for different system situations. The energy based indices can be readily expressed in monetary values and used to study the economic aspects of utilizing unconventional energy sources in terms of fuel savings.

Studies have been conducted for comparative evaluation of conventional SIPS, SIPS including PV, SIPS including WTG, and composite SIPS including both PV and WTG units. The effects on the system cost and reliability of adding different types of energy sources in SIPS with different system compositions have been analyzed. The studies also assess the impact of the variations in different system parameters, such as, the peak load, the penetration levels of unconventional energy sources, the FOR of the generating units, the operating constraints, and the geographic system site selections.

5.2 Effects of Adding Different Types of Energy Sources

The relative benefits of adding different types of energy sources to an example system have been analyzed. The base system is expanded in different ways by adding equal capacity in the form of diesel units, PV arrays, WTG units and combinations of PV arrays and WTG units. The system cost and reliability indices have been compared for the different cases.

The base system taken has two 40 kW and one 70 kW diesel generating units with 5% FOR (MTTF = 950 hours, MTTR = 50 hours). The hourly chronological load shape of the IEEE-RTS [45] has been used in the example system, with a peak load of 60 kW. The system is assumed to be located at a geographic location with atmospheric conditions that can be represented by the Toronto solar radiation data and the Saskatoon wind speed data shown in Appendix C. The IEEE-RTS composite customer damage function (CCDF) has been used in the cost analyses. A total of 40 kW has been added to the base system in each of the four cases as shown in Table 5.1.

Table 5.1: Different Energy Addition Cases

Case	Type of Units	Number of Units	Unit Rating	FOR (%)	MTTF (hours)	MTTR (hours)
1	Diesel	1	40 kW	5	950	50
2	PV	50	810 Wp	2	4380	90
3	WTG	4	10 kW	4	1920	80
4	PV + WTG	25 + 2	ratings shown above			

A comparison of the system risks for the different capacity addition cases is shown in Figure 5.1. It can be observed that the system risk decreases for each case of capacity addition but not to the same degree. Figure 5.2 compares the system degree of comfort as measured by the probability of health for the four cases. The increase in the system health with the addition of different energy sources is also quite different.

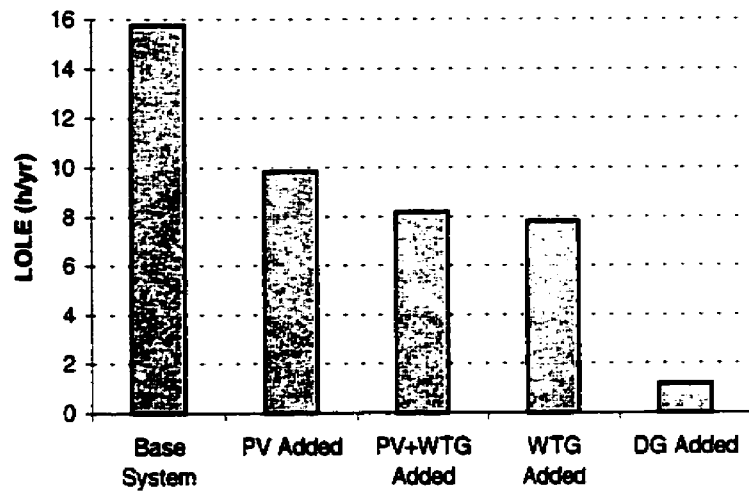


Figure 5.1: System Risk with Different Energy Sources Added

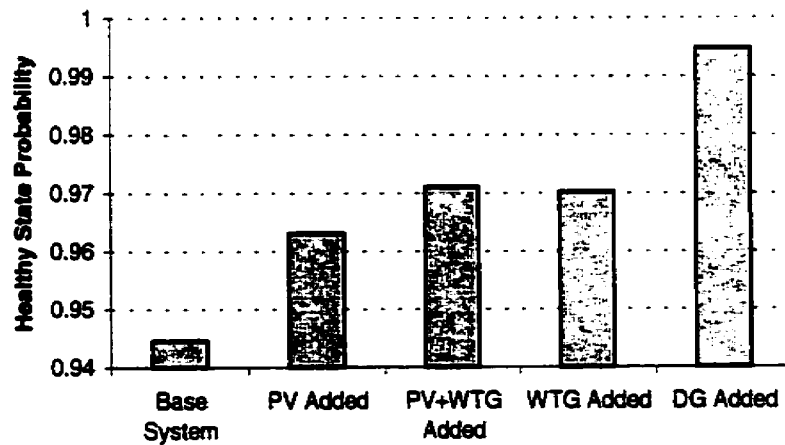


Figure 5.2: System Health with Different Energy Sources Added

Figures 5.1 and 5.2 illustrate that the system reliability improves with the addition of energy sources of any type. The level of improvement is however different, despite equal amount of capacity additions, depending on the type of energy sources added to the

system. The conventional generators are much superior to PV arrays or WTG units when comparing reliability benefits from a given capacity addition. The comparison of reliability from PV and WTG units greatly depends on the data representing the atmospheric conditions at the system location. The addition of WTG provides a better system health and a lower risk than can be obtained from adding equal capacity PV arrays that supply no energy during the night. The reliability benefit when both of these energy sources are included in a composite SIPS is generally between that of PV and WTG additions, depending on the proportion of their penetration levels.

The predicted system reliability can be quite different depending on whether risk indices or health indices are used to evaluate the system. Figure 5.2 indicates that the reliability improvement, in terms of the degree of comfort, is greater when both the PV and WTG units are added together than in the case when only WTG units are added. On the contrary, the reliability benefit, in terms of system risk level, is less for the same situation as shown in Figure 5.1. It is therefore necessary to evaluate the system in terms of both the system health and risk levels.

Figure 5.3 compares the customer interruption costs for the different cases. It can be seen that the customers benefit most when a conventional diesel unit is added to the system. These benefits must be compared with the costs of installing the different units types and operating them, since all the incurred costs will be reflected in the customer tariffs. PV and WTG units in general have relatively high installation costs but they can significantly lower the operating costs as they use free renewable energy to replace costly diesel fuel.

The amounts of diesel fuel that can be saved by adding the different energy sources are shown in Figure 5.4. PV arrays offset only two-thirds the amount of the fuel saved by the WTG units in the example system. The wind energy sources generally save more fuel than PV sources since PV energy is not available during the night. The weather characteristics of the system location, however, have a major effect on the fuel that can be saved by either PV or WTG units.

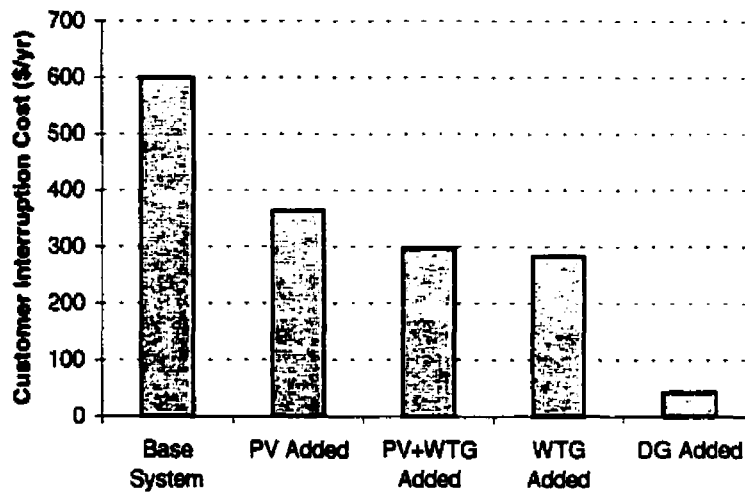


Figure 5.3: Customer Interruption Costs with Different Energy Sources Added

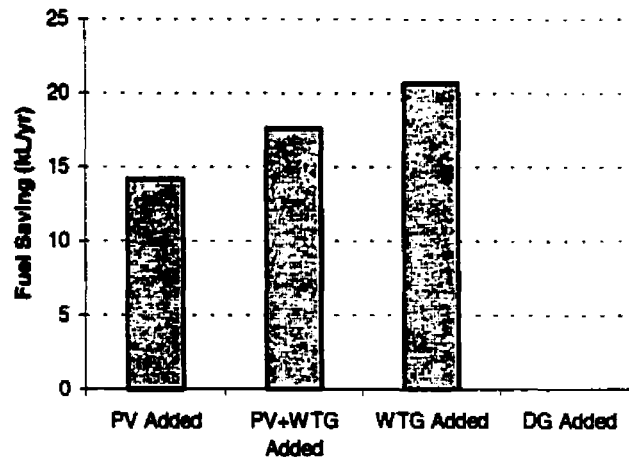


Figure 5.4: Fuel Savings with Different Energy Sources Added

The amount of wind energy that can be supplied to a load in a practical application is restricted by stability concerns. Any dispatch of wind energy to the system load must be accompanied by an amount of conventional energy as specified in the operating

constraints. It has been assumed that no operating constraints exist in the results shown in Figure 5.4. The actual amount of fuel that can be saved by PV and wind energy sources in a practical system will depend on their penetration levels, the weather data at the system site, the operating constraints for the wind system, the load level and the relative difference between the load shape and the time varying energy availabilities from the renewable sources.

5.3 Effects of System Load

The studies on the example system described in Section 5.2 have been extended to analyze the effects of load variations for the four cases listed in Table 5.1. The system peak load was varied from 60 kW to 110 kW while maintaining the original shape of the load curve. The impacts on the system risk and health and on the customer interruption and operating costs have been compared for the four cases.

The variation in the system risk and health are illustrated in the Figures 5.5 and 5.6 respectively. It can be seen that the system risk increases and the system health degrades with load growth for all four composite SIPS. The relative decrease in system reliability is different when different energy sources are included in the system.

It can be seen from Figures 5.5 and 5.6 that there is a relatively large reliability benefit when a conventional unit is added rather than the unconventional sources, and the benefit increases at higher loads. The graphs in Figures 5.5 and 5.6 representing the addition of both PV and WTG units can be compared in the two figures to observe the different impacts on the system risk and health with load growth. Figure 5.6 shows that the mixed sources provide similar system health benefits at both the low and high loads as compared to the addition of WTG units alone. The benefits in the system risk from the mixed sources are seen in Figure 5.5 to be similar to that of the addition of PV units when the peak load is between 70 kW to 90 kW. The different effects on the system risk and health

depend on many factors, such as, the deterministic criterion, the system configuration, the size of the units, the effective capacity of the renewable sources and the effective load.

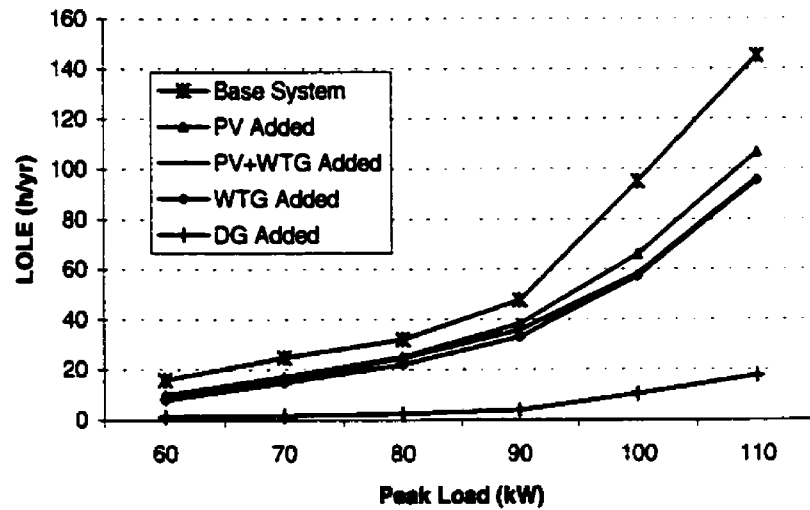


Figure 5.5: System Risk with Load Growth

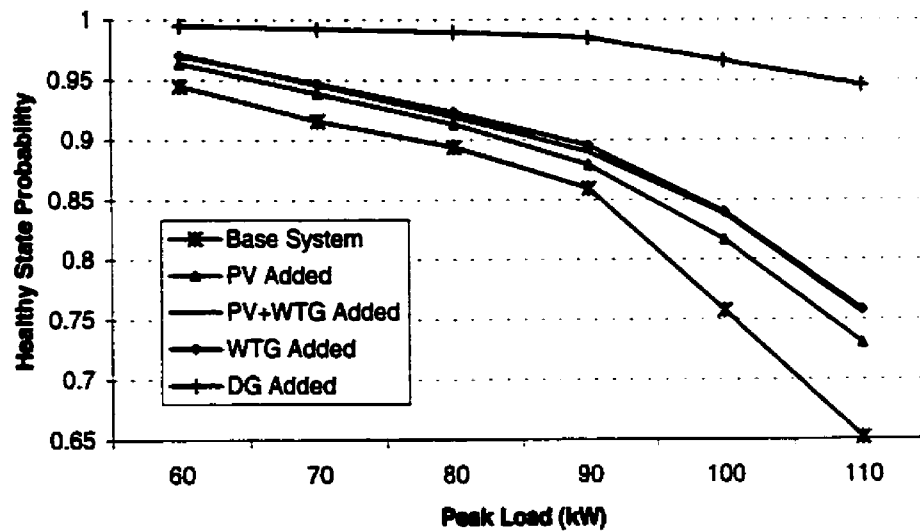


Figure 5.6: System Health with Load Growth

Figure 5.7 compares the customer interruption costs with load growth for the different capacity addition cases. The customer interruption cost increases non-linearly with an increase in system load. Figure 5.7 illustrates that the mix of PV and wind energy sources results in lower customer interruption costs at higher loads when compared to the systems with only PV or WTG unit additions.

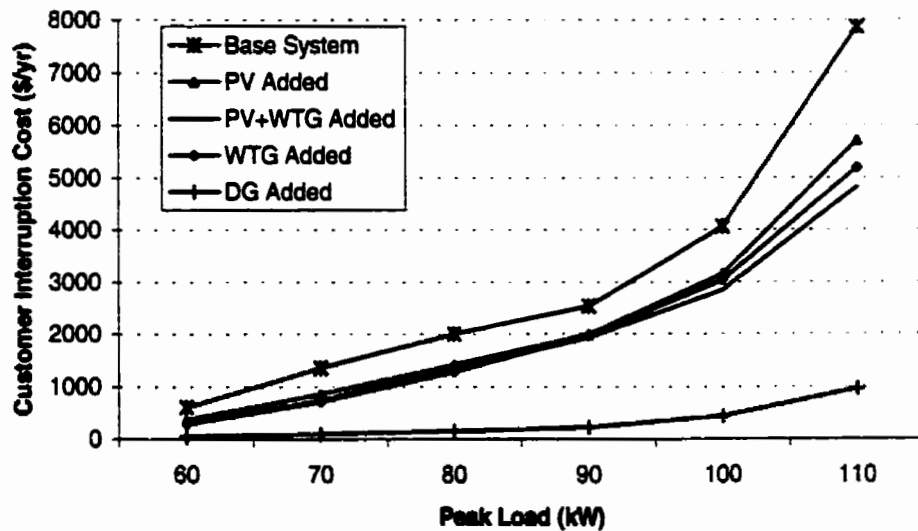


Figure 5.7: Customer Interruption Cost with Load Growth

The amount of fuel saved at different peak load levels when the different types of unconventional energy sources are added is shown in Figure 5.8. The fuel saved in kilolitres remains unchanged as the peak load increases from 60 kW to 110 kW for the cases when WTG units or when a mix of PV and WTG units are added. All the renewable energy generated in these cases are consumed at a peak load of 60 kW. The additional energy required to satisfy any increase in load can only be supplied by the diesel units. The initial portion of the graph for the PV addition case in Figure 5.8 shows a small increase in fuel savings.

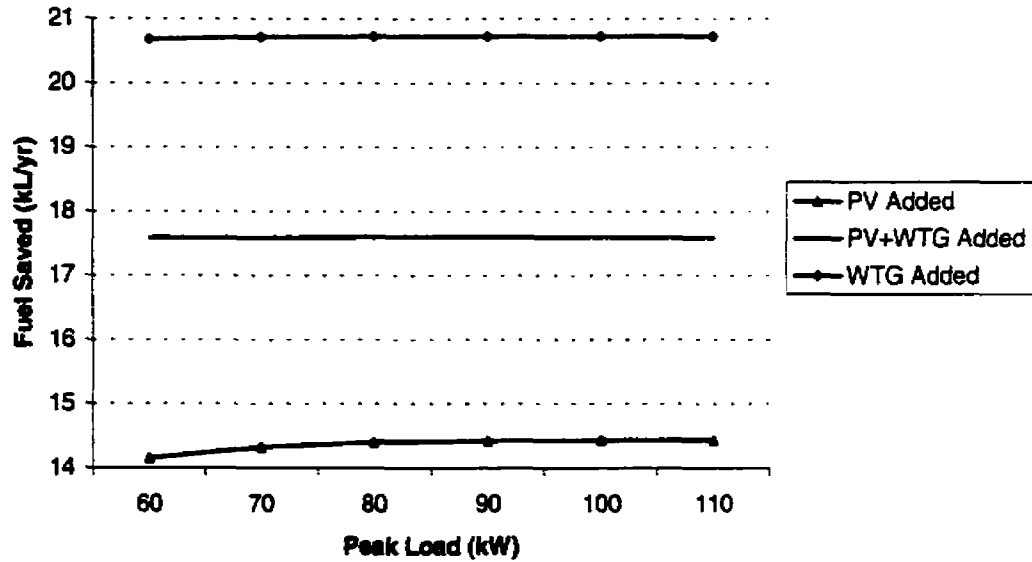


Figure 5.8: Fuel Saving with Load Growth

A maximum fuel saving can be achieved from an unconventional energy source if all the energy generated from it can be utilized. The renewable energy available from these sources may not always be consumed due to a lower instantaneous demand or other operating constraints. The expected surplus energy is the available energy wasted and is shown in Figure 5.9 for the different cases of renewable energy additions. It can be seen that almost all the energy generated has been consumed excepted for the lower loads in the case when only PV arrays are added to the system.

The variation in the system load in the above studies has been modeled by increasing the peak load while maintaining the same load shape. Changes in load factor or in the shape of the load curve will also affect the system reliability and cost indices. Maximum benefit from the unconventional energy sources can be achieved by injecting an appropriate mix of energy sources in order to generate a power output profile that closely matches the load profile. Demand side management techniques can be applied to shape the load curve in order to maximize the utilization of the surplus energy from the renewable sources.

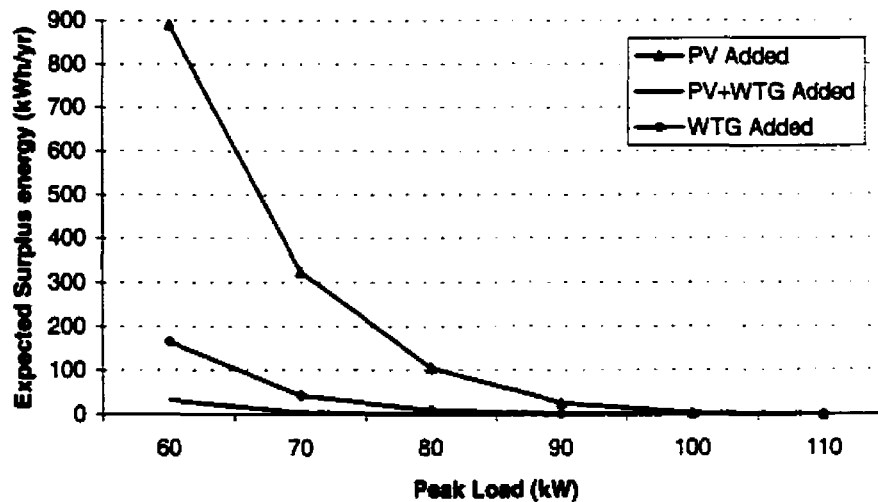


Figure 5.9: Expected Surplus Renewable Energy with Load Growth

5.4 Effects of Penetration Level

Studies have been carried out to analyze the effects on the system cost and reliability of varying the penetration levels of the renewable energy included in the system. The system indices have been computed for the case in which the base system is expanded using a gradual increase of PV energy penetration. Similar studies have been conducted for increasing wind energy penetration. The unconventional energy sources have been added to the base system in equal steps of 20 kW of peak capacity.

The variation in system risk with increasing renewable energy penetration is shown in Figure 5.10. The system risk decreases with an increase in the generating capacity. The decrease in risk is almost linear as the penetration level increases to 60 kW, after which the reliability benefit decreases with further increase. A similar trend can be observed in Figure 5.11 for the degree of system comfort measured in LOHE.

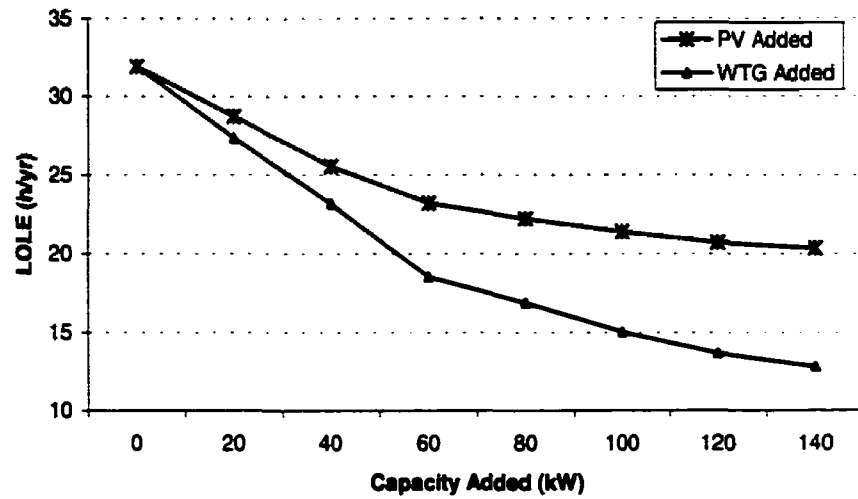


Figure 5.10: System Risk with Increasing Penetration

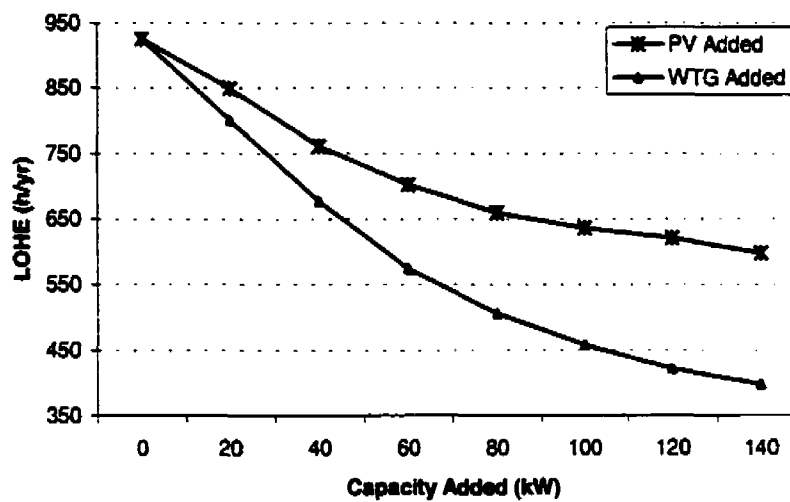


Figure 5.11: System Health with Increasing Penetration

Figure 5.12 illustrates the variation in the customer interruption cost with increase in renewable energy penetration to the example system. The customer interruption cost falls sharply for initial additions but eventually tends to settle out at high penetration levels.

The PV or wind energy penetration should be increased to a level at which the cost of installation is justified by the worth to the customers.

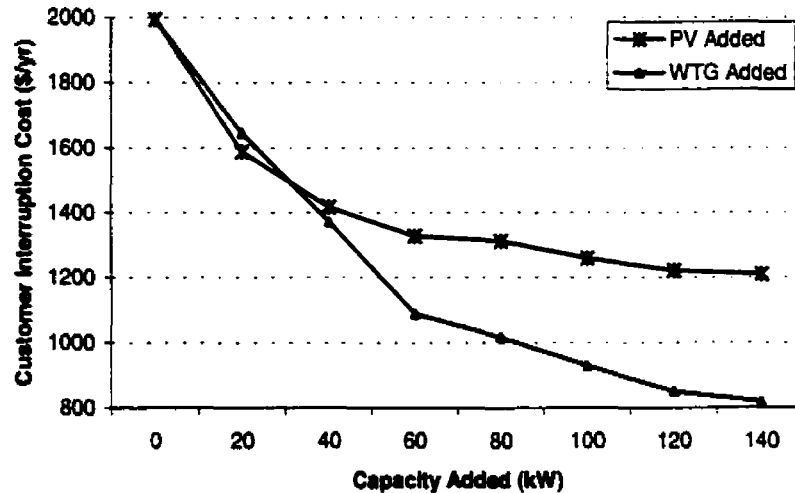


Figure 5.12: Customer Interruption Cost with Increasing Penetration

The system reliability improves with an increase in the renewable energy penetration. The reliability benefit, however, decreases with further addition of PV or WTG units. There comes a point when no further reliability improvement can be obtained by increased renewable energy penetration. The installation cost of PV and wind energy sources are relatively high. The appropriate amount of renewable energy that can be added at a particular location will differ depending on the renewable energy sources available at that location.

The addition of renewable energy sources to SIPS can significantly lower the operating costs in addition to improving the system reliability. Studies should be conducted to determine whether the increase in the penetration level is justified by the increased reliability worth plus the savings in costly fuel. Figure 5.13 shows the amount of fuel saved each year with different PV and wind energy penetrations. The fuel savings

increase linearly with small increase in penetration levels and eventually tend to saturate at high penetration levels. It can be seen in Figure 5.13 that for the example system the WTG units can offset higher volumes of diesel fuel compared to the PV arrays.

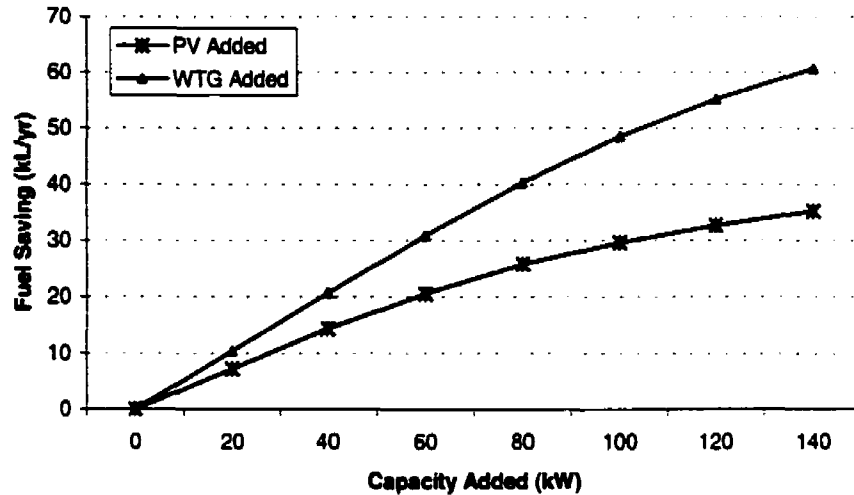


Figure 5.13: Fuel Saving with Increasing Penetration

It is observed from Figures 5.10 – 5.13 that the benefit obtained from adding renewable energy to a system decreases as the penetration levels increase above a certain limit. The reason is that the excess energy available cannot be consumed by the system load. Figure 5.14 shows the expected surplus energy (ESE) in the system with increasing PV and wind energy sources. It can be seen that almost all of the available energy is consumed when the added renewable source capacity is less than 40 kW. The amount of energy wasted increases sharply when more than 80 kW of renewable sources are added to the system.

Figure 5.14 indicates that more energy from the PV sources is wasted compared to the energy from the WTG sources. This is because the availability of wind energy follows the load profile better than the availability of PV energy. The results will be different for different wind and solar radiation patterns and for different load shapes.

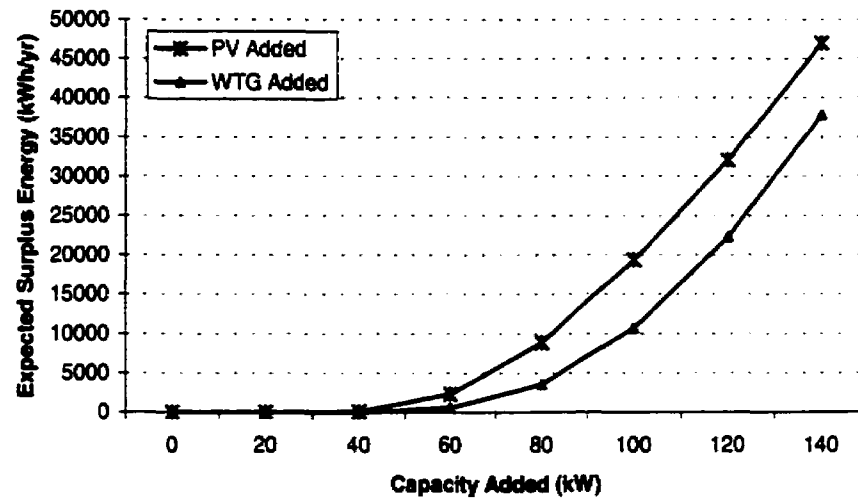


Figure 5.14: ESE with Increasing Penetration

It is impossible to determine the optimum level of renewable energy penetration for systems in general and it is difficult to do this for a given system. This is because the benefits from renewable sources depend on many variables, such as the weather characteristics at the site location, the shape of the load curve, the peak load, the generation system configuration prior to expansion and the types and mix of renewable energy sources that are to be added to the system. An index designated as the Unusable Energy Ratio (UER) has been introduced to help decide an appropriate level of unconventional energy injection. The UER can be calculated using Equation (3.4).

Figure 5.15 illustrates the variation in UER index for increasing amounts of PV and wind energy additions to the example system. The UER for both the PV and wind energy additions up to 40 kW is almost zero. The ratio then increases with the increase in the penetration levels. The UER values with the wind energy additions are smaller than when PV sources are added to the system.

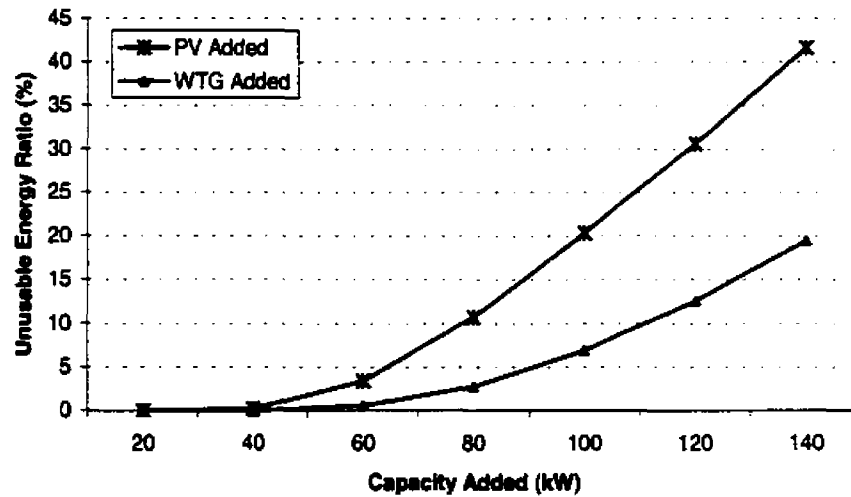


Figure 5.15: UER with Increasing Penetration

An appropriate value of UER can be selected as a criterion to avoid excessive investments in renewable energy sources. The selection of the criterion requires the expertise on the behavior of a composite SIPS and its associated variables, and also on the economics involved. The installation cost and the fuel price will have a major impact in determining the appropriate UER criterion. For example, the renewable energy penetration can be increased to a higher value of UER with significant overall benefits if the installation cost is relatively low and the fuel price is high. The relative benefits from reliability worth aspects must also be considered. The same UER value will produce different amounts of benefits from the PV and the wind energy sources.

5.5 Effects of Unit FOR

The reliability of a power system is strongly influenced by the FOR of the generating units. Accurate MTTF and MTTR values must be used to enable correct evaluation of the system under study. The methods and practice for obtaining these data have been well

established in conventional power systems and historical data are available for various conventional generating unit types and sizes. This is not the case for renewable energy sources. The unconventional units not only lack adequate operational data but also lack an established model to obtain MTTR and MTTF statistics that can be widely accepted.

The effect on the system adequacy of changing the FOR of the different types of energy generating units in a composite SIPS has been studied. PV arrays and WTG units have been added to the example base system as shown in Cases 2 and 3 in Table 5.1. The system indices are compared for the cases listed below:

Case 2 System:

1. Changing the FOR to 0%, 2%, 5% and 10% of the PV arrays only
2. Changing the FOR to 2%, 5% and 10% of one 40 kW diesel unit only

Case 3 System:

1. Changing the FOR to 0%, 2%, 5% and 10% of the WTG units only
2. Changing the FOR to 2%, 5% and 10% of one 40 kW diesel unit only

Figures 5.16 and 5.17 illustrate the variation in the system risk and health with the changes in FOR of the unconventional sources and the diesel units as listed above. It can be seen that the changes in FOR of the unconventional units does not have any significant impact on the system health and risk. The four 10 kW WTG units were replaced by a one 40 kW WTG unit to analyze whether the changes in FOR of a larger unit has any impact on the system reliability. The solid lines shown in Figures 5.16 and 5.17 indicate that the FOR of a renewable energy unit has relatively little effect on the system reliability despite the unit sizes. This phenomenon can be compared with the dotted curves in the figures where the FOR of the diesel unit (that has the same size as the large WTG unit) is varied. The level of reliability degrades sharply with increase in the FOR of the diesel units.

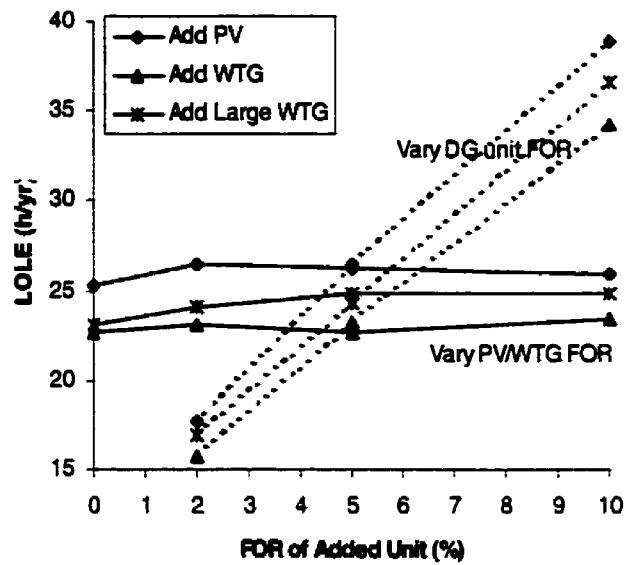


Figure 5.16: System Risk with Unit FOR Variation

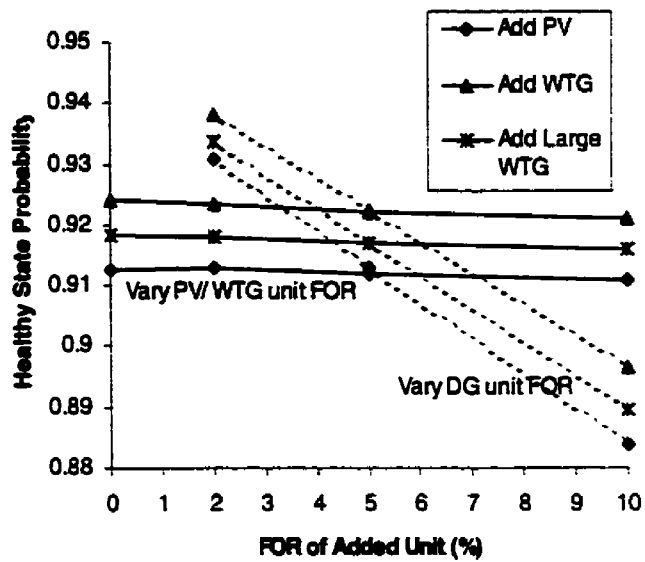


Figure 5.17: System Health with Unit FOR Variation

The energy availability from the unconventional sources is largely dictated by the atmospheric conditions. The rapid fluctuations of the wind speed and the solar radiation mask the effect of expected failures and repairs of the unconventional units when considering the output power from these sources. The FOR of renewable energy sources have therefore relatively little impact on the reliability of the system.

Figure 5.18 compares the customer interruption costs for the different cases of FOR variation. It can be observed that the cost to the customer is basically insensitive to the changes in FOR of the PV arrays or the WTG units. The customer cost increases significantly when the FOR of the diesel unit is increased.

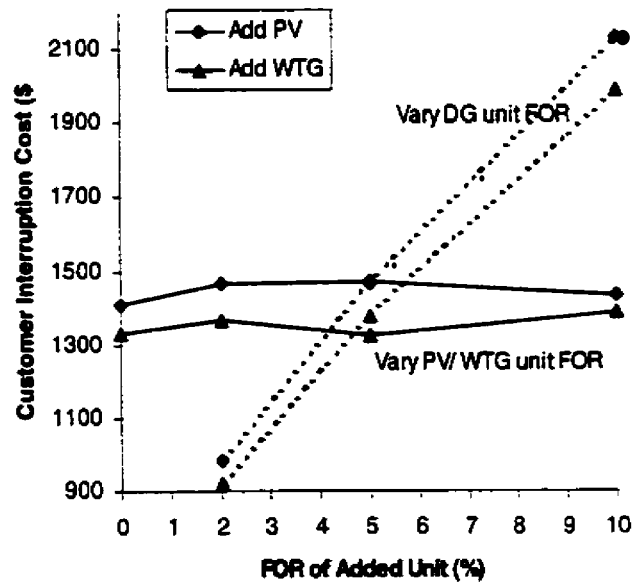


Figure 5.18: Customer Interruption Cost with Unit FOR Variation

It is noted earlier that adequate data on the reliability performance of renewable energy sources are not available. There is no visible benefit from reliability evaluation point of view in devoting considerable effort to obtain highly accurate MTTF and MTTR data for the unconventional sources since the impact of these data on system adequacy is minimal. The results from the above studies also indicate that increasing investment in more reliable PV cells or WTG units does not significantly improve the system reliability.

5.6 Effects of Operating Constraints

It has been discussed in Section 3.4.2 that the inclusion of WTG units has adverse effects on the stability of the system. The amount of load that can be supplied by the wind energy is usually limited in practice by imposing an operating constraint. The constraint level can be selected depending on the nature of the power system and the desired level of service quality.

The studies conducted in the previous sections impose no operating constraints on the wind energy system and assume that all the wind energy available can be consumed to satisfy the system demand. This assumption provides an unrealistically optimistic evaluation of the wind energy. The benefits of adding WTG units in a system are significantly curbed by constraints that must be satisfied in order to maintain system stability. The studies described in this section evaluate the benefits from wind energy with different operating constraint levels.

The base system considered in the examples in Sections 5.2 – 5.5 has been modified by removing one 40 kW diesel generating unit. The other system parameters remain the same. An equal capacity of 80 kW has been added to the base system with five different mixes of PV and wind energy sources. The FOR of the PV arrays and WTG units are given in Table 5.1. The descriptions of the units added in the five different cases are listed in Table 5.2.

Table 5.2: Different Mix of Renewable Energy Additions

Case	Type of Units Added	Number of Units Added	Mix of Capacity Added (kW)
1	All PV	100	80
2	PV + WTG	75 + 2	60 + 20
3	PV + WTG	50 + 4	40 + 40
4	PV + WTG	25 + 6	20 + 60
5	All WTG	8	80

The system indices for the five different system configurations listed in Table 5.2 have been evaluated for the three different operating conditions of; no constraint, a wind to diesel load dispatch ratio (W:D) of 0.67, and a wind to diesel load dispatch ratio of 0.25. The constraint “W:D=0.67” indicates that the wind energy cannot exceed 40% of the system load and the remainder must be supplied by the diesel units. The constraint “W:D=0.25” limits the wind energy to 20% of the system load.

Figure 5.19 compares the system risk for the five different system configurations listed in Table 5.2, using the three different operating constraints. The system risk increases significantly for the systems with a higher mix of wind energy as the operating constraint becomes more restrictive. Figure 5.19 illustrates that an equal mix of PV and wind energy provides the minimum system risk when the operating constraint is “W:D=0.25”, whereas for the other two operating constraints, the PV to wind energy mix of 20:60 is seen to provide the minimum system risk. It can also be observed that the reliability benefit from the WTG units is less than that from the PV arrays for the most stringent constraint shown in Figure 5.19. The figure also illustrates that adding a mix of PV to wind energy in a ratio of 40:40 or 20:60 provides a lower system risk than when adding wind energy alone with a constraint of “W:D=0.67” for a composite SIPS. A W:D ratio of 0.67 is considered to be a practical constraint level [44].

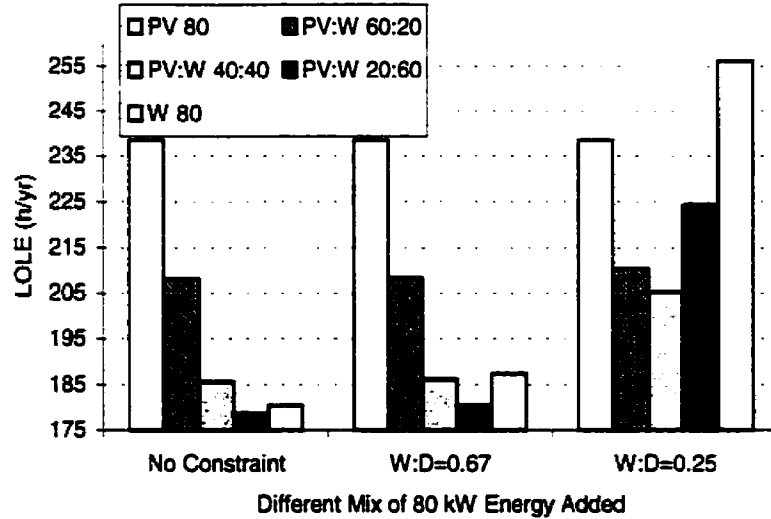


Figure 5.19: System Risk with Different Energy Mix and Operating Constraints

The reliability improvements in terms of system health are illustrated for the different cases in Figure 5.20. The figure shows that the mix of PV and wind energy in the 20:60 ratio provides the maximum probability of meeting the deterministic LLU criterion for all the three operating constraints. This is different from the system risk outcome where Figure 5.19 indicates that the energy mix in the 40:40 ratio provides the minimum risk at the most restrictive constraint. The degree of comfort decreases as the imposed constraint permits less wind energy to be dispatched in all the system configurations that include WTG units.

Figure 5.21 illustrates the variation in the customer interruption cost for the five different energy supply mixes with the three different operating constraints. The results obtained are similar to the variations in the system risk in Figure 5.19. The operating constraint will have a major influence on the expected customer interruption cost in a system containing a significant amount of wind generation.

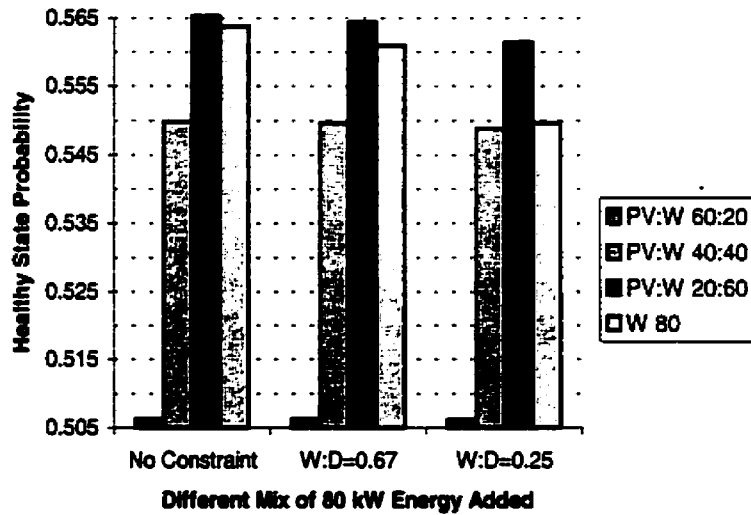


Figure 5.20: System Health with Different Energy Mix and Operating Constraints

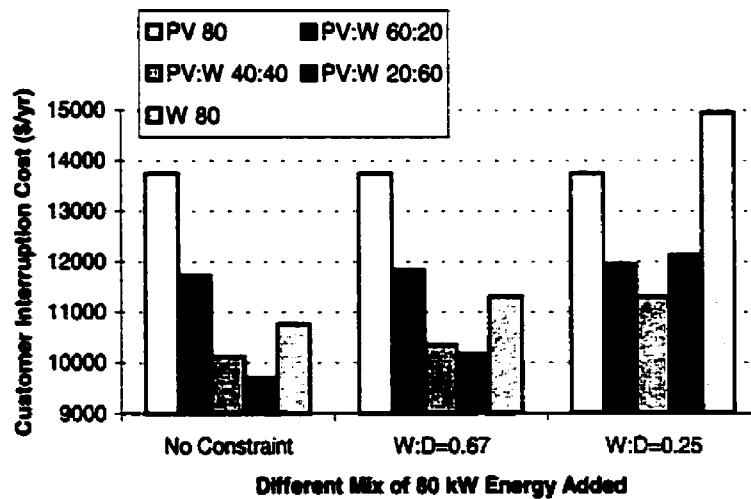


Figure 5.21: Customer Cost with Different Energy Mix and Operating Constraints

The amount of diesel that can be offset by renewable energy for the different energy supply mixes with the three different operating constraints are compared in Figure 5.22. It can be seen that the fuel savings increase with the increased wind energy injection when no constraints are imposed on the wind supply. The amount of fuel that can be offset reduces significantly for higher wind penetrations as the specified stability constraints become more restrictive. A mix of PV and wind supply with a lower wind component will provide a greater fuel saving as the wind energy restriction increases.

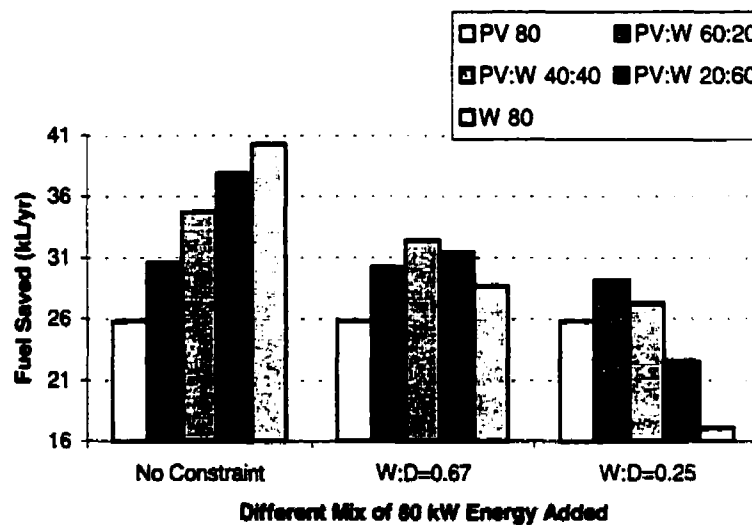


Figure 5.22: Fuel Saved with Different Energy Mix and Operating Constraints

The benefit from utilizing wind energy sources is restricted significantly by the operating constraint imposed to maintain the stability of the system. WTG units can be installed at a much lower investment cost compared to installing PV arrays. A large amount of energy is wasted when only WTG units are injected in a SIPS due to the operating constraint. Other methods of addressing the stability problems in a WTG system is by applying AC-DC-AC conversion and reactive power injection using electronic circuitry. The cost of these additional components can be compared with the savings in the cost of diesel fuel

and the reduction in customer interruption costs due to relaxing the wind system operating constraint. Studies similar to those described in this section can be used to evaluate the optimum mix of PV and wind energy sources, from both the reliability and costs aspects, for a system with a specified operating constraint.

5.7 Effects of Geographic Location

Weather characteristics vary with different geographic locations. Any type of cost or reliability analysis on a composite SIPS requires the necessary data that represent the atmospheric conditions at the selected system site. The impact of the weather patterns on the system reliability and cost have been studied by considering the same system at different geographic locations and comparing their system indices.

The example base system with PV arrays and WTG units added as shown in Cases 2 and 3 in Table 5.1 has been examined to analyze the effect on the system cost and reliability of varying the site atmospheric conditions. The system with WTG units (Case 3) has been considered using the data from five different locations in Saskatchewan Canada: North Battleford, Yorkton, Saskatoon, Regina and Swift Current. The hourly mean wind speed and standard deviation data for these locations have been obtained from Environment Canada and are shown in Appendix C.

Figures 5.23 and 5.24 compare the system risk and health for the same system (Case 3 System) with the wind characteristics for the five different locations. A wind-diesel system situated at a location with a higher mean wind speed has a higher system health and lower risk. Figures 5.23 and 5.24 confirm that a higher reliability can be achieved when a WTG system is installed at the Swift Current location as compared to the reliability obtained from the other four locations. Regina is the next best choice from both the system risk and health aspects.

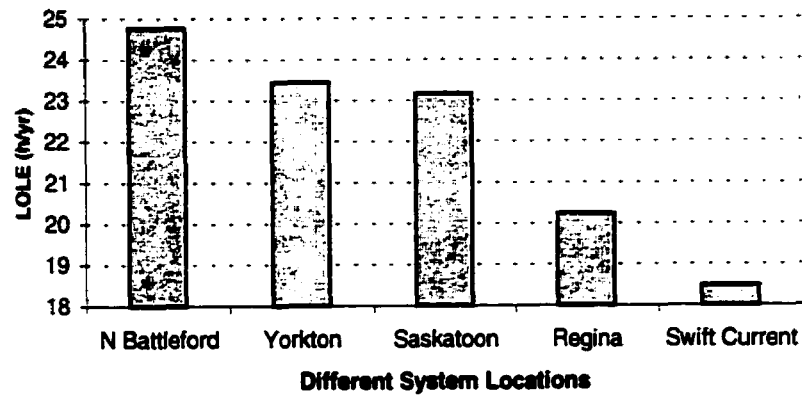


Figure 5.23: System Risk at Different Locations

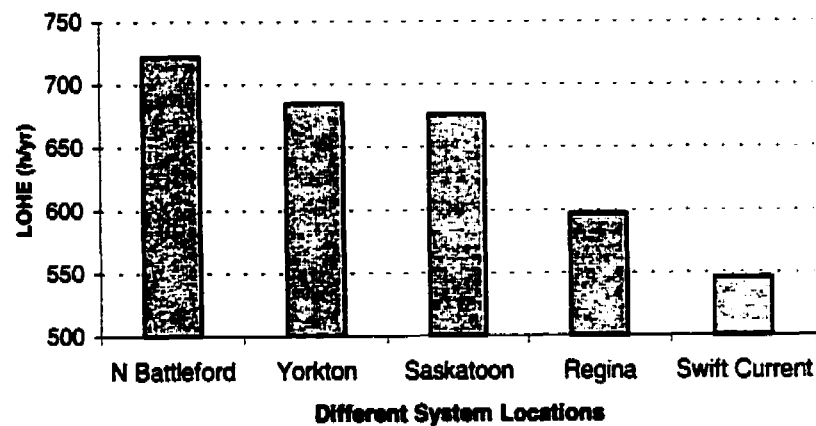


Figure 5.24: System Health at Different Locations

The amount of fuel savings for the wind-diesel system has been compared for the different locations in Figure 5.25. The same system can offset double the volume of diesel when located in Swift Current compared to the case when it is located in North Battleford.

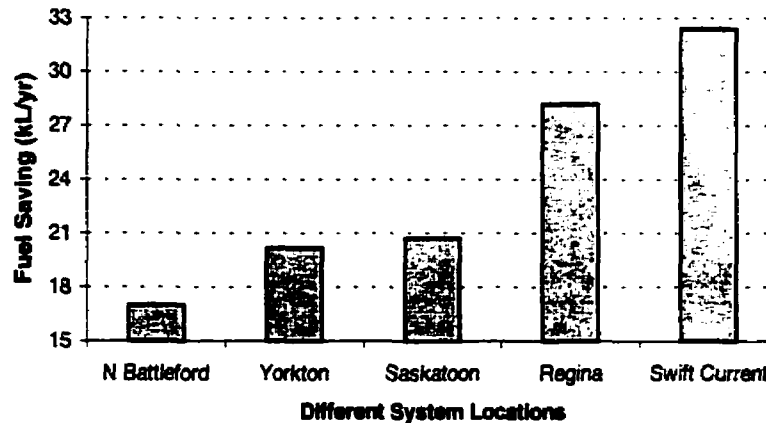


Figure 5.25: Fuel Saving at Different Locations

The benefit obtained by utilizing renewable energy depends heavily on the weather characteristics of the system geographic location. It can be observed from Figures 5.24 and 5.25 that a SIPS located in Swift Current will benefit much more than at the other locations, both in terms of system reliability and fuel costs, by using wind energy. Studies such as these should be conducted to decide the locations where WTG units can be installed for maximum benefit and to evaluate the actual benefit with respect to cost and reliability.

Similar studies at different locations have been conducted for composite SIPS with PV energy. The Case 2 System in Table 5.1 has been considered for six different locations with varying atmospheric conditions. The monthly mean weather data for Swift Current and Toronto have been obtained from Environment Canada and are shown in Appendix C. Hypothetical data have been used for four other sites to study the effects of solar radiation and ambient temperature on composite SIPS containing PV arrays. The hypothetical solar radiation data have been selected from the higher and lower values of typical available data. The monthly mean solar radiation data for Swift Current varies

from 3.78 MJ/m^2 in the month of December to 24.24 MJ/m^2 in July. The data for the hypothetical dark and bright sites have been taken as 8 MJ/m^2 and 22 MJ/m^2 for all the months. Mean temperatures of 0 and 30 degrees centigrade have been assumed for the hypothetical cold and hot sites respectively. The objective in selecting these hypothetical sites is to analyze the effect of site temperature and brightness on the system costs and reliability.

The system risk and health for the Case 2 System at the six different locations have been compared in Figures 5.26 and 5.27 respectively. The figures show that the utilization of PV arrays provides a better system reliability in Swift Current than in Toronto. The system with a higher mean solar radiation can be observed to have a better system reliability. The system reliability can be seen to respond more to the variation in brightness than to the changes in temperature. The ambient temperature has negligible effect on the systems at locations with poor solar radiation. On the other hand, the system reliability can be seen to degrade with the increase in ambient temperature at the locations with higher solar radiation.

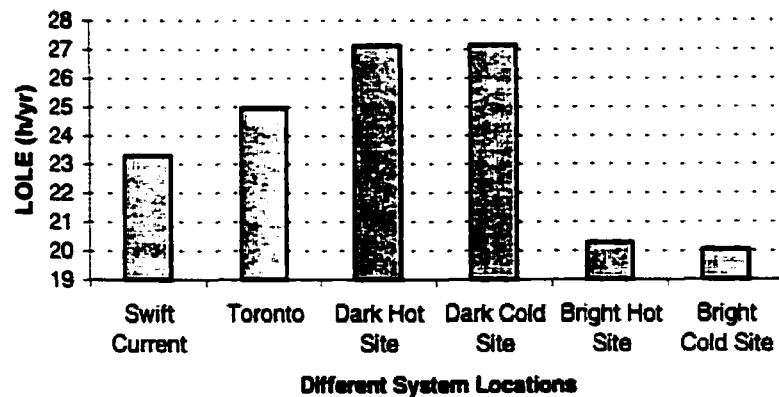


Figure 5.26: System Risk at Different Locations

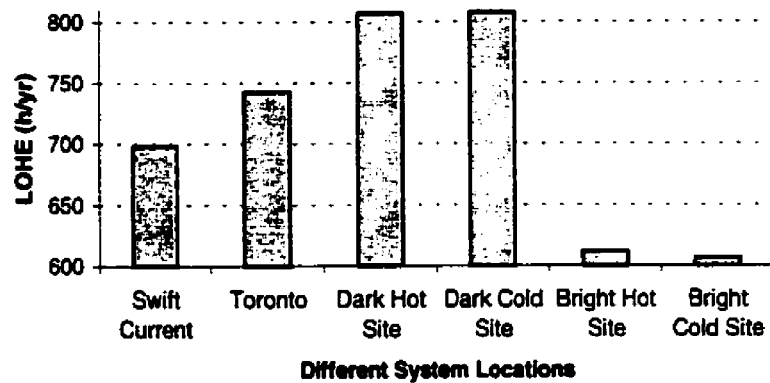


Figure 5.27: System Health at Different Locations

The fuel savings in a system containing PV, located at different geographic sites, can be compared as shown in Figure 5.28. Greater fuel savings can be achieved at locations that have lower temperatures and higher solar radiation. The savings in the operating costs due to fuel offset can be compared at the different locations to help make decisions regarding investment in a particular system site.

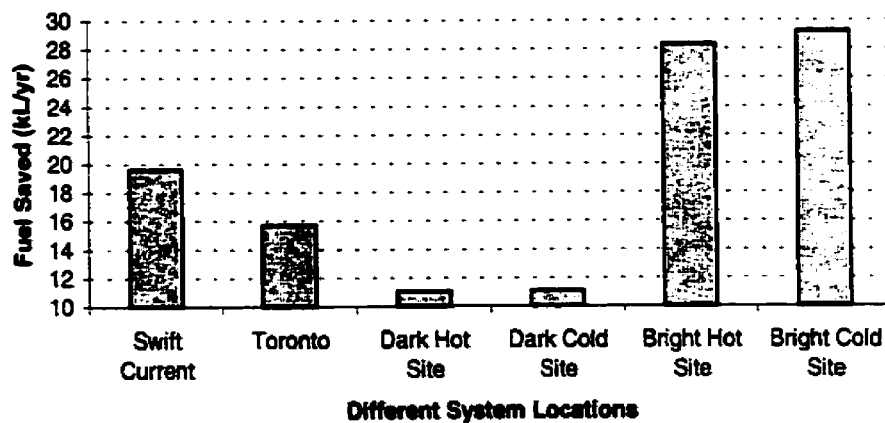


Figure 5.28: Fuel Saving at Different Locations

The level of reliability provided by a composite SIPS and the economic benefits from the fuel offsets can vary widely from one geographic location to another. Contrary to conventional systems, composite SIPS planning and operation decisions are largely dictated by the inherent atmospheric characteristics of the system geographic location. System studies similar to the ones described in this section can be performed by power utilities when deciding where a certain type of renewable energy source can be installed for maximum benefit and what types of sources are best suited to a particular location.

5.8 Conclusion

Composite SIPS reliability and economics is affected by the many different variables that influence the behavior of the system. The studies described in this chapter compare the effects of energy system composition, energy source FOR, load levels, operating constraints and geographic system location on the system indices of composite SIPS with different mixes of conventional and unconventional energy.

The reliability of all types of composite SIPS degrades with increase in the system load. The level of risk increases and the degree of comfort in satisfying the deterministic criterion decreases with load growth. The relative decrease in system reliability is, however, different when different types of energy sources are included in the system. Renewable energy sources will offset more fuel as the load increases given that the system has significant expected surplus energy prior to load growth.

The level of reliability can be increased by installing additional energy sources in a composite SIPS. The different options of adding PV, WTG or diesel units are described in this chapter. The reliability benefits obtained from the addition of conventional generators are much greater than that obtained by an equal capacity addition of PV arrays or WTG units. The relatively high reliability achieved by the diesel units is also accompanied by an increased operating cost due to high fuel consumption. The reliability

benefits from adding PV and WTG units depend on the site-specific weather data. The major benefit of adding renewable energy is the reduction in the system operating costs.

Wind energy is generally a better choice than PV from both reliability and economic considerations. When both of PV and wind energy sources are included in a composite SIPS, the reliability and cost benefits will lie between that of PV and WTG additions depending on the individual penetration levels. The benefits from wind energy sources, however, can be restricted significantly by the operating constraints imposed to maintain system stability.

The operating constraint restricts the amount of wind energy that can be supplied to the load. The more stringent the constraint, the lower will be the benefits achieved from higher wind energy penetration levels. The optimum mix of PV and wind energy sources can be evaluated from both reliability and costs aspects for a system with a given operating constraint. The cost of investing in alternative methods to alleviate the operating constraints can also be compared with the annual savings in fuel costs as a result of the investment.

The addition of renewable energy sources in a composite SIPS can be increased to improve reliability and replace diesel fuel only up to a certain point, after which no further benefit can be obtained. The benefits decrease with increasing penetration levels since more of the renewable energy is wasted. Excessive investments in unconventional sources can be avoided by selecting an appropriate value of UER as a criterion to determine the optimum penetration levels that can be harnessed at a particular system location.

The FOR of a generating unit is an important parameter that affects the reliability of a power system. The reliability of a composite SIPS degrades sharply when the FOR of a conventional unit is increased. Remarkable variations in FOR of the unconventional units, however, do not have significant impacts on the system risk or health. The accuracy in reliability studies of composite SIPS is not greatly affected by lack of accuracy in the

MTTF and MTTR data for the unconventional units. A significant improvement in system reliability cannot be achieved by increasing investment in more reliable PV cells or WTG units.

The weather characteristics of the system geographic location dictate the benefit that can be obtained from renewable energy sources. A wind-diesel system situated at a location with a high mean wind speed offsets more diesel fuel and provides a higher system reliability than one at a location with a lower wind speed. A PV-diesel system provides greater benefits when installed at a site with a high mean solar radiation and low ambient temperature. The effect of temperature is, however, noticeable only at locations with higher solar radiation. The level of reliability provided by a composite SIPS and the economic benefits from the fuel offsets are largely dictated by the inherent atmospheric characteristics of the system geographic location.

6. COMPOSITE SMALL ISOLATED POWER SYSTEM CAPACITY PLANNING CRITERIA

6.1 Introduction

The application of renewable energy in electric power systems has grown rapidly in recent years and is expected to continue to do so in the future. The reliability aspects of utilizing these energy sources have largely been ignored. As these applications further increase, it will be increasingly important to assess the quality of service that can be expected from using renewable energy. A realistic evaluation of the monetary benefits associated with these energy sources also requires an assessment of the level of system reliability that can be obtained when using these sources.

One of the main reasons for ignoring the reliability aspects of renewable energy is that these sources generally only provide a small contribution relative to the conventional generating capacities in major power utilities. The impact on the overall system reliability is therefore generally not significant. The global trend of increased renewable energy penetration in power systems dictates a very serious need to consider their effect on system reliability.

The lack of appropriate reliability techniques is a more practical reason for ignoring the reliability aspects of renewable energy. Unlike large interconnected systems, the renewable energy penetration levels will be much higher in composite SIPS and their effect on the system reliability will be very significant. The majority of small power systems in remote areas use deterministic reliability techniques that cannot incorporate the highly erratic behavior of renewable energy sources.

One objective of using renewable energy sources to supply remote communities is to decrease the electric energy reliance on costly fuel. Cost/benefit analyses should be conducted using comparable standards or levels of electric service reliability. Comparisons of system costs which ignore system reliability are not valid input to decision making processes.

Adequacy techniques and indices that respond to the nature of renewable energy sources should be applied in composite SIPS evaluation. Deterministic methods, conventional probabilistic risk techniques and the well-being approach are compared in this chapter using practical examples. The results of the studies have been analyzed to determine the most appropriate techniques and indices for reliability assessment of composite SIPS.

6.2 Deterministic Methods

Deterministic methods are widely used for reliability evaluation of SIPS. The required system adequacy is expressed in terms of the capacity reserve requirement. The actual capacity reserve in a SIPS can be calculated using Equation (6.1). This capacity reserve should satisfy the criterion expressed in Equation (2.7).

$$CR = \sum_{i=1}^n C_i - PL \quad (6.1)$$

where, C_i = capacity rating of the i^{th} unit
n = total number of generating units
and PL = system peak load.

The problem in applying a deterministic approach to a composite SIPS is in determining the capacity of a renewable energy source. This capacity is not a fixed value as in the case of a conventional unit but is a random variable that rapidly fluctuates with time depending

on the weather characteristics at the system location and the energy conversion parameters.

A simulation method to estimate the expected capacity of an unconventional energy source is presented in the following section. The deterministic criteria represented by Equation (2.7) can be applied to a system with renewable energy sources by utilizing their expected capacities in reserve assessments. Equation (6.1) is modified to Equation (6.2) in order to consider the expected capacities of renewable energy sources in the calculation of system capacity reserve. Equation (6.2) contains the term capacity factor (CF) of a renewable energy unit and is discussed in the next section.

$$CR = \sum_{i=1}^n C_i + \sum_{j=1}^m CF_j \cdot R_j - PL \quad (6.2)$$

where, C_i = capacity rating of the i^{th} conventional unit

n = total number of conventional generating units

R_j = capacity rating of the j^{th} renewable energy unit

CF_j = capacity factor of the j^{th} renewable energy source obtained from Equation (6.5)

m = total number of renewable energy units

and PL = system peak load.

6.2.1 Expected Capacity of a Renewable Energy Unit

An evaluation of the capacity of a renewable energy source should consider the effects of the many different random variables and their inter-relations on the output power at any instant. A MCS method can be used to model the hourly variations in these stochastic variables and to estimate the expected capacity of an unconventional unit and the associated distribution. The expected capacity of a WTG and a PV module can be obtained using Equations (6.3) and (6.4) respectively:

$$\text{Expected Capacity of WTG} = \frac{\sum_{i=1}^{N \cdot h} P_i}{N \cdot h} \quad (6.3)$$

$$\text{Expected Capacity of PV} = \frac{\sum_{i=1}^{N \cdot d} P_i}{N \cdot d} \quad (6.4)$$

where, P_i = power output in the hour 'i'
 N = number of simulated years
 h = number of hours in a year
 d = number of daylight hours in a year.

The expected capacity and the expected annual capacity distribution of an example WTG unit, designated as WTG1, have been evaluated using the MCS approach. It has been assumed that WTG1 has a cut-in wind speed of 14.4 km/h, a rated wind speed of 45 km/h, a cut-out wind speed of 90 km/h and a capacity rating of 40 kW. WTG1 is assumed to be located at a geographic site where the wind characteristics can be represented by the Swift Current wind data (available in files "SWIFTCT.WMN" and "SWIFTCT.WSD" in Appendix C). The expected capacity of the 40 kW unit is 10.602 kW. Figure 6.1 displays the distribution of the annual expected capacity about the mean capacity value.

The expected capacity of an unconventional energy unit can be normalized by its capacity rating to compare units of different sizes. An index designated as the Capacity Factor (CF) can be calculated using Equation 6.5:

$$\text{Capacity Factor} = \frac{\text{Expected Capacity}}{\text{Rated Capacity}} \times 100\% \quad (6.5).$$

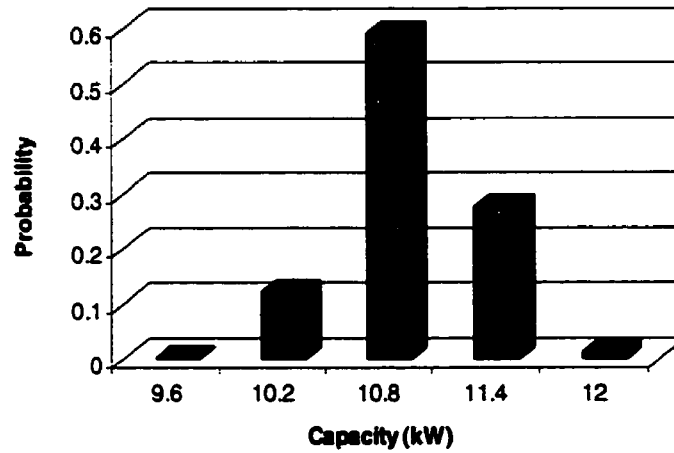


Figure 6.1: Expected Annual Capacity Distribution of WTG1

The capacity factor of an unconventional unit varies from one geographic location to another. Figure 6.2 compares the capacity factors of the wind energy unit WTG1 at different locations. The wind data for the different locations are given in Appendix C.

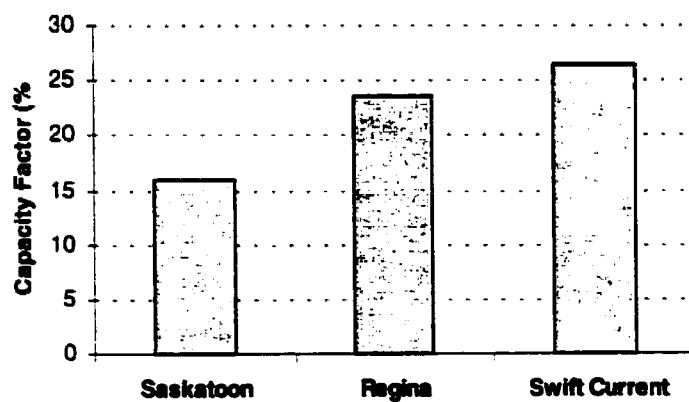


Figure 6.2: Comparing the Capacity Factors of WTG at Different Locations

The expected capacity of a renewable energy unit also depends on its design characteristics. The capacity factors of two WTG units with different design characteristics are compared in Table 6.1. Both units are considered to be at the same geographic location.

Table 6.1: Capacity Factors of WTG Units with Different Design Characteristics

ID #	Wind Speed Characteristics (km/h)			Rating (kW)	Expected Capacity (kW)	Capacity Factor (%)
	Cut-in	Rated	Cut-out			
WTG1	14.40	45.00	90.00	40	10.602	26.51
WTG2	11.16	46.80	192.96	40	12.335	30.84

PV arrays cannot supply power during the night. The expected capacity of a PV unit can be calculated using Equation (6.2) by considering the power output during the daylight hours. It has been assumed that the total number of daylight hours is half the total hours in a calendar year.

A PV array consisting of 9 groups of 3 modules in series has been considered at a location (50.3° N latitude) in Swift Current. The array is tilted at an angle equal to the latitude. The monthly mean global solar irradiation, wind speed and ambient temperature data are stored in a data file named "SWIFTCT.WTH". The module specification data is available in the data file "CANROM30.ARR" shown in Appendix C. The rated capacity of the PV array is 810 Wp (9 x 3 x 30 Wp modules). The expected capacity of the array at the given location is 292.31 W. The expected annual capacity distribution is shown in Figure 6.3.

The capacity factor for the above case is compared with the case when the PV array is installed at a location in Toronto (43.4° N latitude). This location has an atmospheric condition represented by the data provided in the file "TORONTO.WTH" in Appendix C.

Figure 6.4 compares the capacity factors of the same PV array at the two different geographic sites.

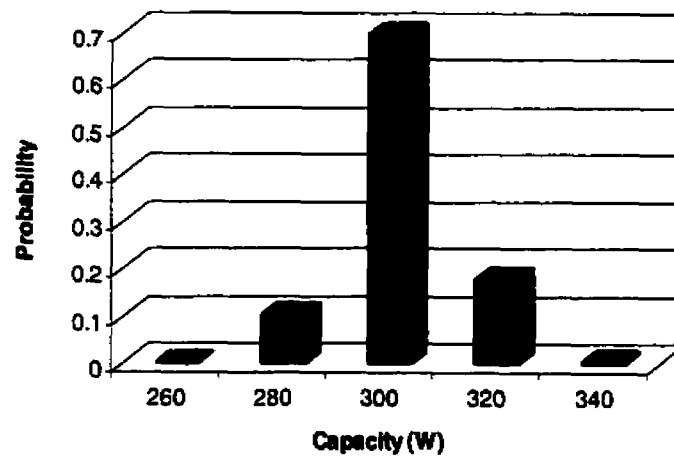


Figure 6.3: Expected Annual Capacity Distribution of a 810 Wp PV Array

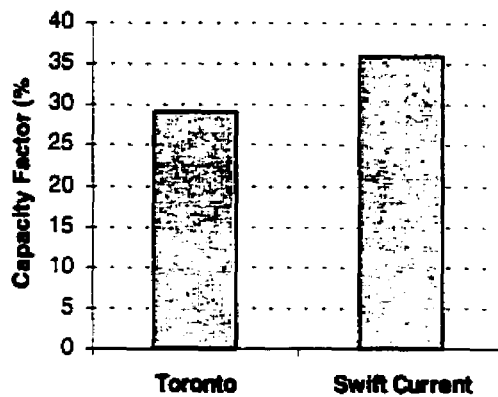


Figure 6.4: Comparing the Capacity Factors of a PV Array at Different Locations

The proposed MCS method of evaluating the expected capacity of a renewable energy source can consider the inherent complexities of dependency of the various random variables that influence the power output. The expected capacity varies considerably with changes in the geographic location and the energy conversion source parameters. The expected capacity provides an equivalent capacity measure of a renewable energy source. The distribution of the expected capacity of an unconventional unit at a certain location can also be obtained for different hours throughout the day using the MCS technique.

6.2.2 Problems with Deterministic Methods

System planners routinely apply deterministic techniques in reliability evaluation of SIPS. These methods cannot be easily extended to determine the capacity requirements when renewable energy sources are also included, due to the highly erratic nature of their power output. The power output of a renewable energy unit fluctuates rapidly between zero to the rated value in vast contrast to a conventional unit that can provide a relatively steady power output. Most system planners do not have methods to incorporate renewable energy sources in capacity requirement studies of composite SIPS.

One way to incorporate renewable energy sources in conventional capacity requirement studies is to use their expected capacities. The capacity factors for different types of renewable energy sources can be found for a particular system location. The expected capacities for different levels of renewable energy penetration can then be calculated by multiplying the rated capacity by the corresponding capacity factor. The capacity requirement analysis must be done separately for daytimes and the nighttimes, when PV sources exist in the system. A straight forward method cannot be applied as in the case of conventional systems when renewable energy sources are included in a system.

The adequacy of a system is influenced by the many factors which act on it. These factors cannot be reflected in any way using the existing deterministic methods. Some of these

factors are the forced outage rates of the generating units, uncertainties in the forced outage rates, the probability of residing in different derated states, energy limitations, planned maintenance of units, the system load factor, the shape of the load curve, the uncertainty in load forecasting, operating constraints, etc. Additional random variables, which cannot be recognized by the deterministic techniques, are introduced in the system when renewable energy sources are included. Some of these variables are the random chronological variations of the weather, their effects on the renewable energy sources, the unconventional unit parameters that influence energy conversion efficiency, etc. Probabilistic methods must therefore be used to incorporate the effect of all these factors in the adequacy evaluation. The system risk indices and well-being indices can be evaluated to analyze the effects of the various stochastic variables on the system reliability.

The capacity factors of unconventional units can be used in deterministic approaches to adequacy evaluation of composite SIPS. These techniques are not, however, recommended since they cannot recognize the behavior of a system that is driven by numerous random variables. The evaluation of the capacity factor of the unconventional units requires a significant computation effort. It is more advantageous to extend the MCS to include the load characteristics and obtain the adequacy indices directly instead of obtaining the expected capacities to use in a deterministic approach.

6.3 Probabilistic Methods

The prediction of the future behavior of a power system that is influenced by different random system parameters can only be recognized using probabilistic techniques. The existing probabilistic risk methods and the newly developed well-being methods are applied to composite SIPS in this section. The assessments of the system from the two different approaches are compared to determine the more appropriate technique for composite SIPS evaluation.

Most large systems with conventional power generating plants apply probabilistic risk approaches for generation adequacy evaluation. These techniques can also be applied to composite SIPS to assess the system planning risk.

Application of the probabilistic risk methods are illustrated using an example composite SIPS. The example system has two 40 kW and one 70 kW diesel units with 5% FOR. The system also includes a 40 kW WTG with a cut-in wind speed of 14.4 km/h, rated wind speed of 45.0 km/h, cut-out wind speed of 90.0 km/h and a FOR of 4%. The system has a peak load of 80 kW with an hourly load profile similar to that of the IEEE-RTS. The system is located at a site with wind characteristics that can be represented by the Swift Current data given in Appendix C. Five different cases have been studied with a specific change in the base example system for each case.

Case 1: The FOR of the diesel units are changed from 5% to 2%.

Case 2: The load factor is changed to 100%.

Case 3: The WTG design characteristics are changed to a cut-in wind speed of 11.16 km/h, a rated wind speed of 46.80 km/h and a cut-out wind speed of 192.96 km/h. The system peak load is changed to 81.5 kW.

Case 4: An operating constraint is imposed to limit the use of wind energy within 20% of the total demand at any instant in order to maintain system stability.

Case 5: The system location is changed to a site that has the North Battleford wind characteristics. The system peak load is changed to 79 kW.

The capacity reserve in each of the five different cases meets the criterion of the CLU + 13.25% PL. Figures 6.5 and 6.6 show that the probabilistic methods indicate different levels of reliability in each case.

Figure 6.5 illustrates the changes in the system risk for the five different case studies. The changes in Cases 1 and 2 result in the maximum differences in the system risk. The factors that have been varied in the first two case studies will influence the risk in all types of power systems. Cases 3, 4 and 5 involve changes in factors that do not exist in conventional power systems. The effect of these factors on the wind energy source creates the changes in the system risk as shown in Figure 6.5. The effects of these factors will be more profound when a higher penetration of renewable energy sources exists in the system.

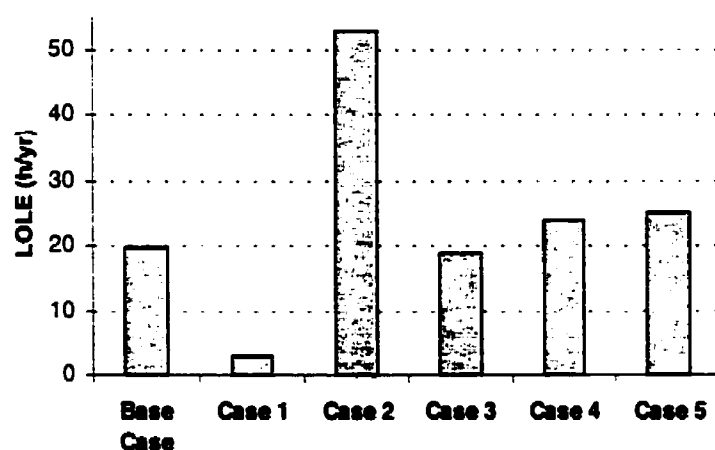


Figure 6.5: Changes in System Risk for the Case Studies

The probabilistic risk methods respond to the effects of different random variables in a composite SIPS. These techniques, however, do not provide any indication of the reserve margin in the system. The lack of system operating information in the risk indices, and the concern in interpretation of risk as a measure of system adequacy have made SIPS planners reluctant to use these methods.

The system well-being approach incorporates a specified deterministic criterion in a probabilistic framework. This approach has been applied to the five different case studies

in the previous example. Figure 6.6 shows the changes in the system health for the different cases when the loss of the largest unit (LLU) is taken as the specified deterministic criterion. The response of the well-being approach is very similar to that of the probabilistic risk methods.

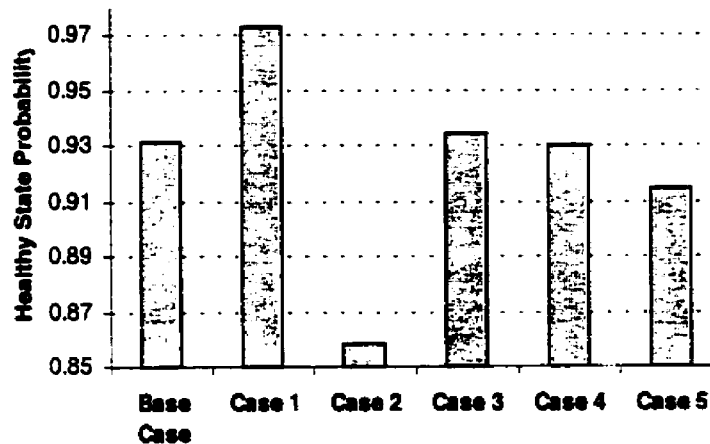


Figure 6.6: Changes in System Health for the Case Studies

The major advantage of the well-being indices over the risk indices is that they also provide information on the system operating reserves in addition to recognizing the effects of the stochastic system variables. The well-being indices should, therefore, prove to be more useful to SIPS planners.

The system adequacy improves when additional capacity is installed in the system. The types and sizes of the added units affect the level of improvement in the system reliability. The quantitative assessment of system reliability using the probabilistic risk method has been compared with the well-being approach by applying the two methods to the example system described in Table 6.2.

Table 6.2: An Example SIPS

Generation	2*40 kW, 1*70 kW diesel units, 5% FOR
Load	80 kW peak load, IEEE-RTS hourly load shape
Site	Swift Current wind characteristics

Different sizes of WTG units with a cut-in wind speed of 14.4 km/h, rated wind speed of 45 km/h, a cut-out wind speed of 90.0 km/h and a FOR of 4% have been added separately to the example system in Table 6.2. The capacity factor for the given WTG unit at the system location is 26.5%. The system health and risk have been compared for the example system when a single WTG unit is added with increasing capacity ratings as shown in Figure 6.7.

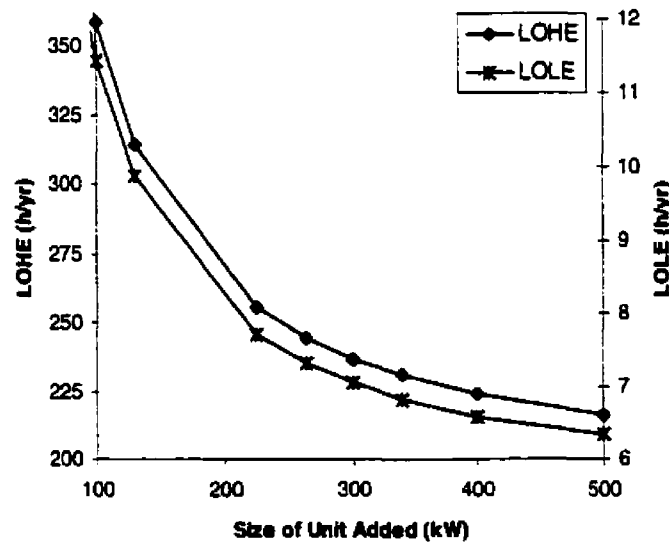


Figure 6.7: System Health and Risk with Size of Added WTG Unit

The system health is expressed in terms of LOHE in Figure 6.7 in order to facilitate the comparison with the widely used risk index LOLE. The comparison is more difficult to appreciate if the healthy state probability is used to measure the system health due to two

factors; the system health and risk are inversely related to the system reliability, and due to the differing scales and units of measurement.

Figure 6.7 illustrates that the system health and risk are affected in a similar manner when a WTG unit of any rating is added to a SIPS. The LLU criterion specified for the healthy state drives the system health index to respond to the size of the units in the system configuration. The health and risk indices respond similarly to a WTG addition because of the almost continuous distribution of the wind energy source capacity.

Figure 6.8 compares the health and risk indices when different PV penetration levels are added to the example system given in Table 6.2. The installation of different numbers of PV arrays, each consisting of nine groups of three 30 Wp modules in series, have been considered at the system location. The module specification data is available in the data file "CANROM30.ARR" and is shown in Appendix C. The LOHE and the LOLE have been evaluated for the added capacities rated in kWp as shown in Figure 6.8.

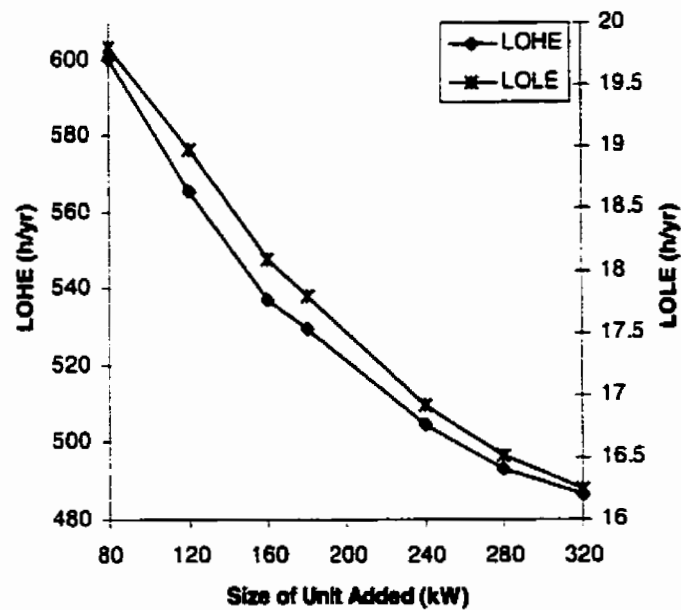


Figure 6.8: System Health and Risk with Size of Added PV Array

The next study considers the addition of a diesel generating unit with 5% FOR to the example system in Table 6.2. Figure 6.9 compares the system health and risk indices when a single unit with different capacity ratings is added.

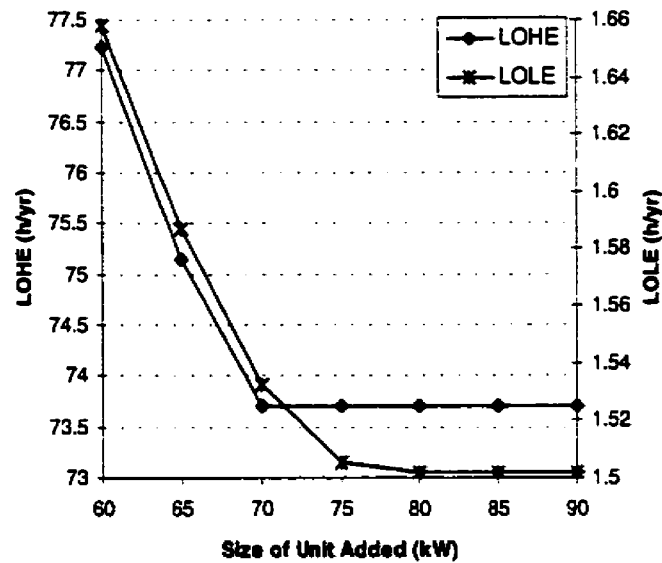


Figure 6.9: System Health and Risk with Size of Added Diesel Unit

It can be observed from Figure 6.9 that the system reliability improves both in terms of health and risk when a large unit is added to a system. The system health and the risk indices, however, behave differently when a unit with a capacity rating larger than the capacity of the largest unit is added to the system. The capacity of the largest unit is 70 kW in this example. The system health does not improve by adding a unit larger than the capacity of the largest unit since the LLU has been taken as the deterministic criterion for system health. The system risk continues to fall even when the unit size exceeds the capacity of the largest unit. Figure 6.9 shows that the system risk does not decrease any further when the size of the added unit exceeds 80 kW.

The comparison of the results in the Figures 6.7 – 6.9 indicates that a greater improvement in system reliability can be achieved by adding a diesel unit to the system. The achievable reliability benefits are much lower with the addition of renewable energy sources. The benefits in terms of the system health and risk can be different depending on the configuration of the generating system and the deterministic criterion that dictates the healthy condition. The differences in the system health and risk behaviors increase when larger discrete capacity levels exist in the system capacity distribution, and as capacity units larger than the CLU are added to the system. The system health benefits are smaller than the risk benefits when adding large conventional units. The capacity distribution is more continuous with renewable energy sources and causes less differences in the health and risk indices.

The system health and risk indices can respond quite differently to various factors at different times during the operation of a composite SIPS. The application of risk indices alone has not been readily accepted in SIPS evaluation although the indices do provide useful quantitative risk measures. System health indices provide additional operating information and can be used jointly with the risk indices in reliability studies of a composite SIPS.

6.4 Dual Criteria Approach

Probabilistic techniques must be applied to recognize the various random variables inherent in a composite SIPS in order to conduct a realistic evaluation of system reliability. The studies in the preceding section show that both the probabilistic risk and well-being methods respond to the different stochastic system parameters and provide quantitative measures of their system reliability impacts. The degree of comfort in satisfying a specified deterministic criterion such as the LLU, and the risk of failing to meet the system demand are two distinctly different aspects of system reliability.

System planners attempt to make sure that the quality of power supply does not degrade to an unacceptable level at any time. The reliability will decrease with time as the system load increases if additional facilities are not provided.

The existing reliability criteria used in SIPS are largely deterministic and are not very useful when renewable energy sources are included in the system. The deterministic criteria can, however, be used to determine the system health in well-being applications. A specified index of system health can then be used as a useful reliability criterion. An alternate option to maintain an acceptable level of system reliability is to use a risk criterion similar to that normally used in large interconnected systems.

The use of separate risk and health criteria in capacity planning of a composite SIPS are compared by applying them to an example system. The example system has three 40 kW diesel units with a FOR of 5%. The hourly load shape for the system is represented by the IEEE-RTS chronological hourly load data. The peak load is assumed to be 72 kW in Year 0. The load growth over a period of six years is shown in Table 6.3.

Table 6.3: Peak Load Forecast for the Example System

Year	0	1	2	3	4	5	6
Peak Load (kW)	72	83	95	110	127	147	170

The capacity reserve in Year 0 is 48 kW (i.e. 120 kW – 72 kW), which is approximately equal to the capacity of the largest unit (i.e. 40 kW) plus 10% of the peak load. This is the criterion used by most Canadian utilities in SIPS capacity planning [5]. The system risk and health in Year 0 have been taken as the accepted adequacy criteria in the example studies. The LOLE in Year 0 is 37.67 h/yr. The LOHE is 776.04 h/yr (i.e. a healthy state probability of 0.911167).

It has been assumed that the system planner has decided to add a 70 kW WTG unit followed by a 70 kW diesel unit to the example system at the appropriate times to maintain the system reliability within the accepted levels. The WTG unit has a cut-in wind speed of 14.4 km/h, rated wind speed of 45 km/h, a cut-out wind speed of 90.0 km/h and a FOR of 4%. The system location is assumed to have the Swift Current wind characteristics as given in Appendix C. The diesel unit has a FOR of 5%.

Figure 6.10 illustrates the system risk with increasing load as the WTG and the diesel units are added to the example system. The vertical drops in the figure indicate the additions of new generating units to the existing system. Figure 6.10 shows that the WTG unit must be added in Year 1, the diesel unit in Year 2 and additional capacity must be added in Year 6 to maintain the system risk within the accepted LOLE criterion of 37.67 h/yr.

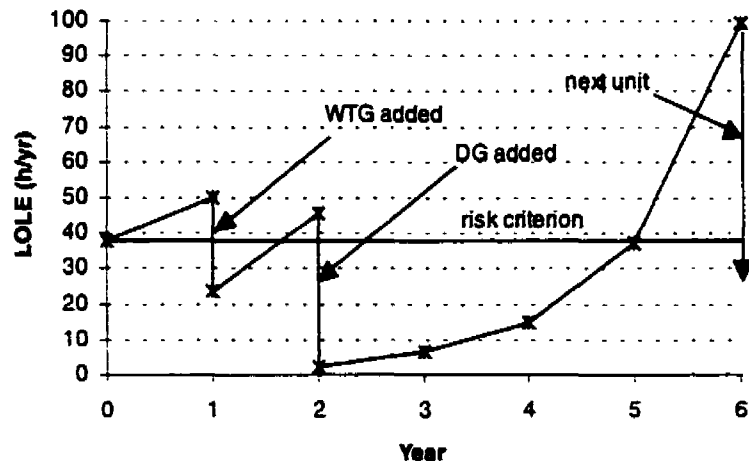


Figure 6.10: Generating Unit Additions to Maintain the System Risk Criterion

Figure 6.11 shows the degree of comfort in meeting the specified deterministic criterion when the new units are added in the sequence shown in the Figure 6.10. It can be seen

that the healthy state probability in Year 5 will be less than the acceptable level at Year 0. The study indicates that a capacity expansion plan based on maintaining a consistent system risk can violate the level of comfort that is required to meet the specified deterministic criterion.

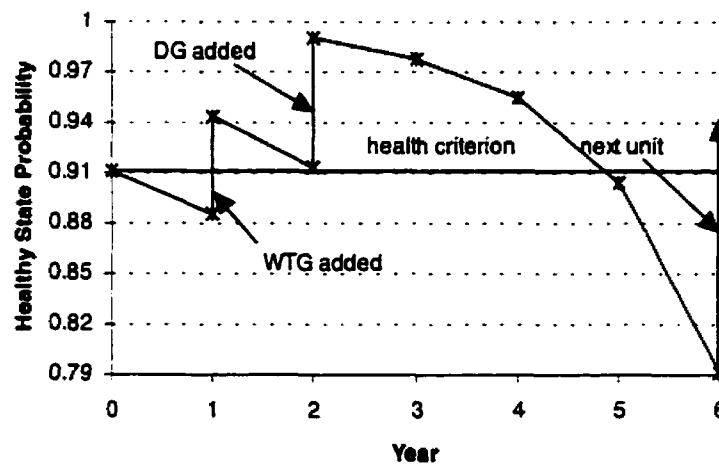


Figure 6.11: System Health with Capacity Expansion Based on the Risk Criterion

Figure 6.12 illustrates the system health with increasing load as the WTG and the diesel units are added to maintain the system health above the accepted healthy state probability criterion of 0.911167. It shows that the WTG unit must be added in Year 1, the diesel unit in Year 3 and additional capacity must be added in Year 5.

The levels of risk in the example system when the new generating units are added to maintain the health criterion are shown in Figure 6.13. It can be seen that the system risk in Year 2 is higher than the acceptable level. A capacity expansion plan based on maintaining a consistent degree of system comfort can violate the acceptable system risk level.

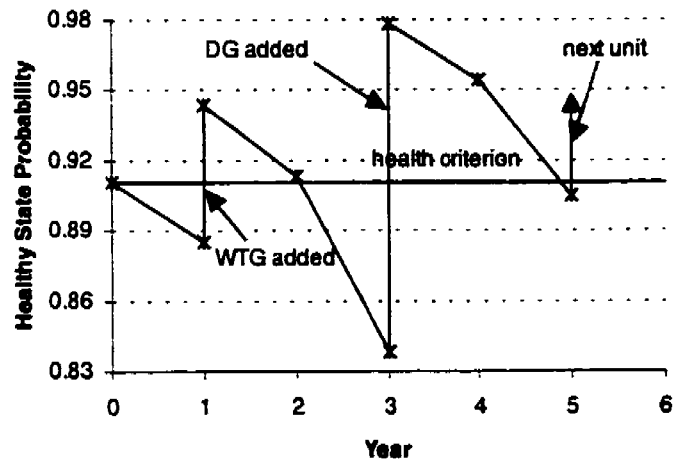


Figure 6.12: Generating Unit Additions to Maintain the System Health Criterion

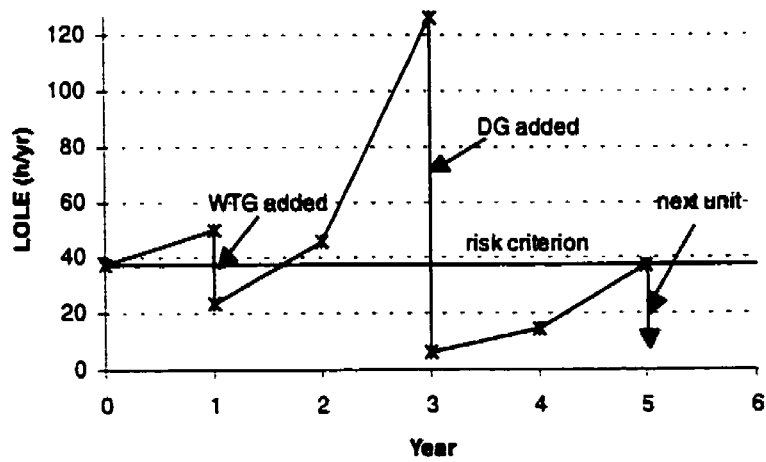


Figure 6.13: System Risk with Capacity Expansion Based on the Health Criterion

The capacity expansion study for the example system shows that the unit addition dates to maintain a consistent system risk are different from the dates required to maintain a consistent system health. The times when the additional generating units must be brought into operation for the two methods are compared in Table 6.4.

Table 6.4: Dates for Unit Addition by Risk and Health Methods

Reliability Criterion	Dates for New Generating Unit Addition		
	70 kW WTG Unit	70 kW Diesel Unit	New Unit
Risk	Year 1	Year 2	Year 6
Health	Year 1	Year 3	Year 5

Table 6.4 shows that the WTG unit must be added in Year 1 from both the system risk and health criteria. The diesel unit must be added in Year 2 to meet the risk criterion. The risk criterion will be violated if the unit is added in Year 3 as required by the health criterion. On the other hand, a new generating unit must be added in Year 5 to meet the health criterion. Adding the new unit in Year 6 as required by the risk criterion will violate the acceptable health limit in Year 5. A dual criteria method using the acceptable limits of both the system risk and health can be used in order to satisfy both conditions.

Figure 6.14 illustrates the application of the dual criteria method to the example system. The LOHE has been used as the system health index instead of the healthy state probability in order to provide easier comparison with the widely used risk index of LOLE. Both the LOLE and LOHE indices have the same measurement units (i.e. hours/year) and they both respond in the same y-axis direction to changes in the system reliability.

In the dual criteria method, both the system risk level and the degree of comfort are monitored continuously with the load growth in order to check whether either criterion has been violated. The system can exceed either the acceptable risk limit or the health

limit or both at any point in time. The generating capacity must be expanded by bringing a new unit into operation before the first violation occurs in either adequacy criterion. Figure 6.14 illustrates that both the risk and health criteria are violated in Year 1 and the WTG unit is brought into operation at that time. The risk criterion is then violated in Year 2, which is a year before the health criterion is violated. The new diesel unit must therefore be installed in Year 2. The health criterion is violated in Year 5 and that is when the next new unit must be added to the system to maintain the acceptable levels of both system risk and health.

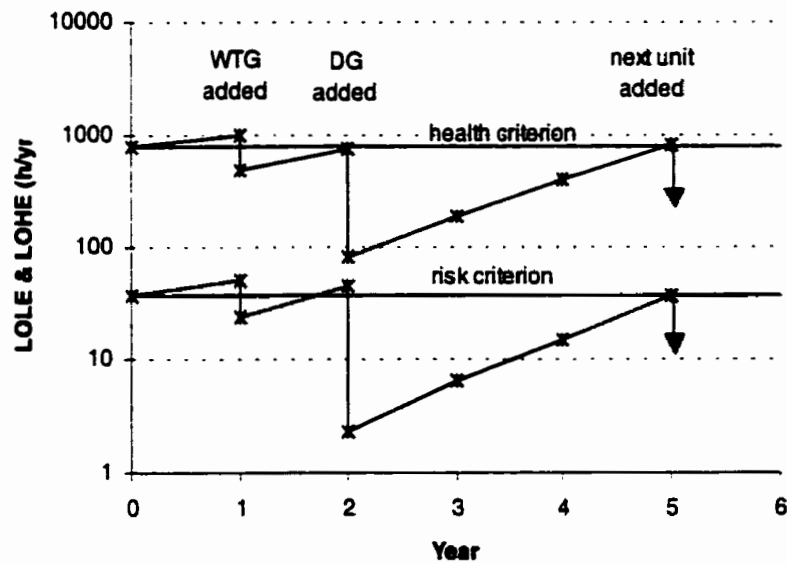


Figure 6.14: Dual Criteria Method

6.5 Conclusion

Reliability assessment of composite SIPS must be conducted using evaluation techniques and indices that best respond to the nature of the renewable energy sources. The deterministic methods, the conventional probabilistic risk techniques and the well-being

approaches have been compared to determine the most appropriate techniques and indices for reliability assessment of composite SIPS.

The existing deterministic methods cannot be directly applied to a composite SIPS since the capacity of a renewable energy source is not a fixed value as in the case of a conventional unit but is a random variable that rapidly fluctuates with time. The expected capacity of an unconventional unit can be estimated using a MCS technique. The capacity factor is the ratio of the expected capacity to the rated capacity of a renewable energy source and depends on the weather characteristics at the system location and the energy conversion parameters.

The basic weakness of the deterministic methods is that they cannot recognize the random behavior of a system. Probabilistic techniques must be applied in some form to recognize the numerous random variables that influence the operation of a power system containing renewable energy sources. Large utilities normally use system risk criteria, such as the LOLE, in capacity planning. The utilization of a single risk index has not been widely accepted in SIPS evaluation despite its utilization in other areas.

An existing deterministic criterion can be incorporated in a probabilistic well-being approach and used in adequacy studies of a composite SIPS. The system health indices provide useful information by evaluating the degree of comfort in satisfying the specified deterministic criterion. Both the system health and risk indices provide useful information but from different aspects of system reliability.

The different factors acting on a composite SIPS can cause the system health indices to respond in a different manner than the risk indices. The changes in the system health and risk depend on the configuration of the generating system. The system health benefits are generally smaller than the risk benefits when large conventional units are added. A system risk criterion is more restrictive than the health criterion when adding relatively small generating units to a system. The capacity distribution is more continuous for renewable

energy sources and causes less distortion in the health and risk indices. The system can violate the degree of comfort required to meet the deterministic criterion if only the risk criterion is used to drive capacity planning in a composite SIPS. On the other hand, the system can be exposed to unacceptable levels of risk when only the health criterion is used. The dual criteria method jointly uses both the health and risk criteria to ensure that the system is reliable from both aspects. Capacity planning using both LOLE and LOHE criteria can prove valuable in practical generation capacity expansion planning of composite SIPS.

7. GENERATION EXPANSION PLANNING

7.1 Introduction

Demand for electrical energy normally increases with time. Load forecasting techniques are used to predict future load growth using data from past experience and the expectation of increased utilization in the future. The supply reliability of a given power system decreases as the system load increases. The system generating capacity must therefore be increased to meet the new load demand and maintain an acceptable level of system reliability.

There are numerous different possible options for expanding the generating capacity of a system. The major challenge faced by system planners is to determine the optimum expansion plan that provides the maximum benefits at the lowest cost over a specified period of time. The optimum utilization of renewable energy to satisfy growing energy needs in composite SIPS further complicates the problems faced in capacity planning.

A wide range of different factors that affect the system performance must be considered prior to installing additional generating units in an existing system. The investment in the capacity expansion and the level of reliability achieved are greatly influenced by the various types, sizes and mix of energy sources and their installation dates. Capacity planning involves studies of the effects of all of these different factors on the economy and reliability of a system, in order to make decisions on the optimum schemes for system expansion.

The capacity of a composite SIPS can be expanded by installing additional PV arrays, WTG units, diesel units or a combination of these energy sources. The costs associated with diesel generating units were provided by ATCO Electric Limited. The costs associated with the WTG units and PV arrays were obtained from References [15] and [47] respectively. These data are approximate figures that depend on many factors and are continuously changing with time. These data, however, provide practical results for the studies conducted. The monetary values used in the cost studies are in Canadian dollars.

An overall cost and worth evaluation must be done to achieve the maximum possible benefits from capacity expansion. The costs of installing renewable energy sources are higher than those of diesel generating units. Possible financial incentives and government subsidies for the installation of renewable energy sources should also be taken into account. It has been observed from the study results in Chapter 5 that the addition of renewable energy sources provides a much lower reliability benefit than the addition of diesel units. On the other hand, the renewable energy sources provide huge savings in operating costs since they offset the costly fuel consumed by the diesel units. The costs and benefits from PV energy must also be compared with wind energy and with a mix of both energy sources.

The basic purpose of generation expansion is to meet the load requirement with a consistent level of system reliability. A dual criteria method is proposed in the previous chapter as an appropriate reliability evaluation technique that can be applied in composite SIPS capacity planning. The method jointly uses risk and health criteria and ensures that the system is not exposed to unacceptable levels of risk and that the system meets the specified deterministic criterion with a reasonable degree of comfort at all times. This chapter illustrates the utilization of the dual LOLE and LOHE criteria in capacity expansion planning of a composite SIPS.

7.2 Example System

Generation expansion of a composite SIPS is illustrated using the small practical system introduced in Chapter 5. The specifications of the generating units are shown in Table 7.1. The system peak load is 60 kW. It has been assumed that the per unit hourly chronological load for the system is the same as that of the IEEE-RTS.

Table 7.1: Generating Units in the Example System

Type	No. of Units	kW Rating	FOR (%)	MTTF (h)	MTTR (h)
diesel	2	40	5	950	50
diesel	1	70	5	950	50

The example system is assumed to be located at a remote geographic site with atmospheric conditions that can be represented by the weather data provided by Environment Canada for Swift Current, situated at a latitude of 50.3° N. The monthly mean global solar irradiation, wind speed and ambient temperature data are stored in a data file named "SWIFTCT.WTH". The hourly mean wind speed and the standard deviation data are available in the files "SWIFTCT.WMN" and "SWIFTCT.WSD" respectively. The contents of these files are described in Appendix C.

The example system supplies electrical energy to meet the needs of a small rural community. The consumers in this community consist of residential customers, commercial customers and governmental institutions, such as a school. It has been assumed that the energy demand in the residential, commercial and government sectors are 40%, 40% and 20% respectively of the total community demand. The costs of different interruption durations were obtained from customer surveys in the different consumer sectors and are shown in Table 7.2.

Table 7.2: Customer Interruption Cost Data for the Example System

User Sector	Sector Demand	Customer Interruption Cost in CAN \$/kW						
		1 min	20 min	1 hr	2 hrs	4 hrs	8 hrs	24 hrs
Residential	40 %	0.001	0.0278	0.1626	0.9878	1.8126	4.0006	18.2491
Commercial	40 %	1.8847	5.5764	15.065	31.6023	75.904	121.9645	146.9024
Government	20 %	2.1585	3.2655	7.2297	11.5795	21.365	44.0597	70.1317
CCDF	100 %	1.1860	2.8948	7.5370	15.3519	35.3596	59.1980	80.0869

The data [46] for the residential and commercial sectors were obtained from a 1991 survey and for the government sector from a 1995 survey. The data for the one-minute and four-hour interruption durations were not available in the 1991 survey and were taken from a previous survey and by interpolation respectively. The missing data for the government sector were approximated using the 1995 survey data from the industrial sector. Reference [46] states that the customer interruption costs in the industrial sector compare most closely with those for the government sector. The last row of Table 7.2 provides the composite customer damage function (CCDF) for the example system obtained by combining the data for the three consumer sectors for all the different interruption durations. The interruption cost per kW for each sector is weighted by the corresponding sector demand and summed to obtain the overall system interruption cost per kW for the particular duration. The CCDF for the example system is shown in Figure 7.1.

It has been assumed that the load demand for the example system increases by approximately 10% every year. The annual peak load (PL) forecast for the next 10 years is shown in Table 7.3. Year 0 is the present year for which the system load is 60 kW.

Table 7.3: Annual Peak Load Forecast for the Example System

Year	0	1	2	3	4	5	6	7	8	9	10
PL (kW)	60	66	73	80	88	97	107	118	130	143	157

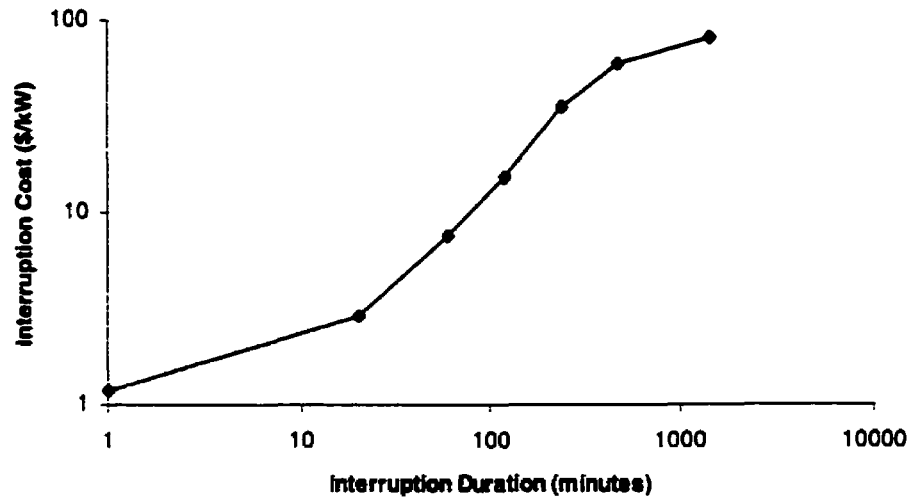


Figure 7.1: CCDF for the Example System

The reliability of the system can be described in terms of the system risk and health. The LLU has been taken as the accepted deterministic criterion for the system health analysis. The system LOLE and LOHE in Year 0 are 15.73 h/yr and 484.68 h/yr respectively. These values of LOLE and LOHE have been taken as the criterion values for the example system.

Additional generating units must be installed in the example system to meet the forecast load growth. The new installations can either be PV arrays, WTG units, diesel units or a combination of these energy sources. The additional energy sources deemed to be available to the system planner are shown in Table 7.4.

The WTG unit listed in Table 7.4 has a cut-in wind speed of 14.4 km/h, a rated wind speed of 45 km/h and a cut-out wind speed of 90 km/h. Each PV array consists of 9 groups of 3 series Canrom 30 Wp modules. The module specification data is available in the data file "CANROM30.ARR" and is shown in Appendix C.

Table 7.4: Additional Energy Sources for the Example System

Type of Energy Source	Unit Rating	FOR (%)	MTTF (hours)	MTTR (hours)
Diesel Unit	20 kW	5	950	50
WTG Unit	40 kW	4	1920	80
PV Array	810 Wp	2	4380	90

The costs associated with the installation and operation of diesel, PV and WTG units must be known. The different cost data used in analyzing the expansion of the example system are listed in Table 7.5.

Table 7.5: Cost Data for Diesel, PV and WTG Units

Unit Type	Unit Cost (\$/kW)	Installation Cost (\$/kW)	Maintenance Cost	Heat Rate (kWh/liter)	Fuel Cost (\$/liter)
Diesel	300	600	0.02 \$/kWh	3.2	0.7
WTG	1500	450	22.5 \$/kW	-	0
PV	11000		0	-	0

A wide range of reliability studies has been performed on the example system to analyze the effects of various factors on system capacity expansion. Selected expansion plans have been analyzed to provide comparative studies of cost and reliability.

7.3 Determining Capacity Expansion Dates

The system load growth and the consequent decrease in the level of system reliability is a function of time. It is therefore very important to determine at what point in time the system capacity must be expanded. The additional energy generating sources must be brought into operation before the system reliability drops below the acceptable limits.

A major problem in reliability studies is to determine the acceptable level of adequacy for a particular system. Most utilities decide the appropriate criteria based on past experience. The accepted risk criteria in most large interconnected power systems vary from 1.0 h/yr [3] in the industrialized countries to 2 days/yr in the developing nations [28]. A reasonable risk criterion for composite SIPS is difficult to determine since adequate data from past experience is not available. The system health index, such as the LOHE or the healthy state probability, has yet to be applied in practice in order to assess acceptable adequacy levels in terms of these indices.

The objective of expanding the generation capacity in a conventional system is to improve the system reliability or to lower the customer interruption costs. Any investment in generation facilities must be justified by its worth to the customers. Reliability cost and worth analysis are conducted by comparative assessment of fixed and variable system costs and customer interruption costs. The total societal cost is the sum of the installation, production, maintenance and customer interruption costs. The objective of the system planner is to achieve minimum total system cost when alternatives are available for any operation or planning scheme. The system reliability at the minimum societal cost can be considered as the optimum level.

The costs incurred and the worth obtained by increasing and decreasing the generation capacity of the example system in the present year are compared in Table 7.6. The capacity expansion in this study includes only conventional diesel generating units. The different costs incurred in a period of one year in the installation, operation and maintenance of the diesel units are calculated using the rates given in Table 7.5. The installation cost is a one-time investment and has been distributed over the effective life of 20 years.

A system has an optimum level of reliability when its generation configuration provides the minimum societal cost. Table 7.6 shows that the societal cost is minimized when no units are removed or added to the base example system. The corresponding system

LOLE is 15.73 h/yr and LOHE is 484.68 h/yr. The customer interruption cost in Table 7.6 is very small compared to the other investment costs. The effect of the customer interruption cost has been found to be insignificant in the cost analysis of a composite SIPS.

Table 7.6: Comparison of Reliability Cost and Worth

Configuration of Example System	Installed Capacity (kW)	Fuel Consumed (liter/yr)	Unit Installation Cost (\$/yr)	Operation Cost (\$/yr)	Customer Interruption Cost (\$/yr)	Total Societal Cost (\$/yr)
Removing a 40 kW unit	110	100100	4950	76477	6605	88032
Base Example System	150	100598	6750	76857	628	84235
Adding a 20 kW unit	170	100632	7650	76883	90	84623
Adding 2-20 kW units	190	100638	8850	76887	22	85759

The expansion of a generating system by adding unconventional energy sources provides a much lower improvement in system reliability compared to the addition of conventional generating units. The primary motive in installing additional PV arrays or WTG units may be to lower the system operating costs rather than to improve the system reliability. Table 7.7 compares the different costs and worth of adding PV and wind energy sources to the example system in the present year.

Table 7.7 shows that the system operating costs decrease significantly with the addition of the renewable energy sources and have a large impact on the total societal costs. The addition of PV arrays increases the societal cost due to their relatively high installation costs. The increase in the installation cost of the WTG unit is compensated for by decrease in the fuel cost and therefore the WTG addition provides the lowest societal

cost in Table 7.7. The optimum system configuration is the one that provides the minimum societal cost at a specified point in time. The customer interruption costs are relatively small in a composite SIPS, as seen in Table 7.7, and therefore do not have any major impact on the overall system cost analysis.

Table 7.7: Reliability Cost and Worth Comparison with Renewable Energy

Configuration of Example System	Installed Capacity (kW)	Fuel Consumed (liter/yr)	Unit Installation Cost (\$/yr)	Operation Cost (\$/yr)	Customer Interruption Cost (\$/yr)	Total Societal Cost (\$/yr)
Base Example System	150	100598	6750	76857	628	84235
Adding 40 kW WTG	190	83902	10650	65001	443	76094
Adding 40 kWp PV	190	86459	29025	66055	442	95522

Table 7.7 also shows that it is economically justified to add 40 kW of WTG to the existing system due to the savings in fuel costs. The addition will also improve the system reliability and possibly provide some capacity to meet the future load growth.

In addition to the available generating capacity planning option, generation expansion is also affected by market economy factors, such as interest rates, inflation and other factors that influence the system costs. The present value of money is less when an investment is made at a later date. It is always beneficial to postpone the installation of conventional units whenever possible. On the other hand, the earlier the installation of renewable energy sources, the higher will be the savings in fuel costs. The interest on the installation of PV arrays or WTG units must be compared with the fuel cost savings to determine the most suitable installation date.

7.4 Determining Types of Energy Sources

The generating capacity of a power system is expanded to meet the increasing demand by installing additional generating units. The new installations considered in this work can either be diesel units, PV arrays, WTG units or a combination of these energy sources. The system planner is faced with the challenge of deciding the installation of the most appropriate types of generating sources at the right times to achieve the maximum overall benefits.

The system reliability must be maintained above the acceptable level with the addition of the selected energy generating sources. Separate studies have been conducted to analyze the addition of diesel units, WTG units and PV arrays to the example system in Table 7.1 in order to meet the load growth as given in Table 7.3. The diesel units to be added are 20 kW in size and their specifications are given in Table 7.4.

The diesel unit additions required to maintain the system adequacy at the accepted criteria (LOLE of 15.73 h/yr and LOHE of 484.68 h/yr) are illustrated in Figure 7.2. The figure shows that an additional diesel unit must be installed in Years 1, 5, 7 and 9 in order to maintain the system reliability over a planning period of 10 years. The vertical drop in the LOHE and LOLE curves indicates the addition of a new generating unit.

The system reliability is very responsive to the addition of conventional generating units. The desired level of adequacy can always be obtained by adding the appropriate number of conventional units at the proper times. Installation of diesel generating units is a very important capacity expansion option in a composite SIPS from a system adequacy aspect.

Figure 7.3 illustrates the additions of WTG units to the example system to meet the load growth. It has been assumed that all the wind energy available can be supplied to the load when demanded. WTG units of 40 kW capacity are added to maintain the system reliability at the accepted risk and health criteria of $\text{LOLE} = 15.73 \text{ h/yr}$ and $\text{LOHE} =$

484.68 h/yr respectively. Figure 7.3 shows that an additional unit must be installed in Year 1, Year 3 and Year 4, and three new units must installed together in Year 5 in order to maintain the accepted adequacy level. The desired reliability level cannot be achieved in Year 6 despite the addition of a large number of WTG units.

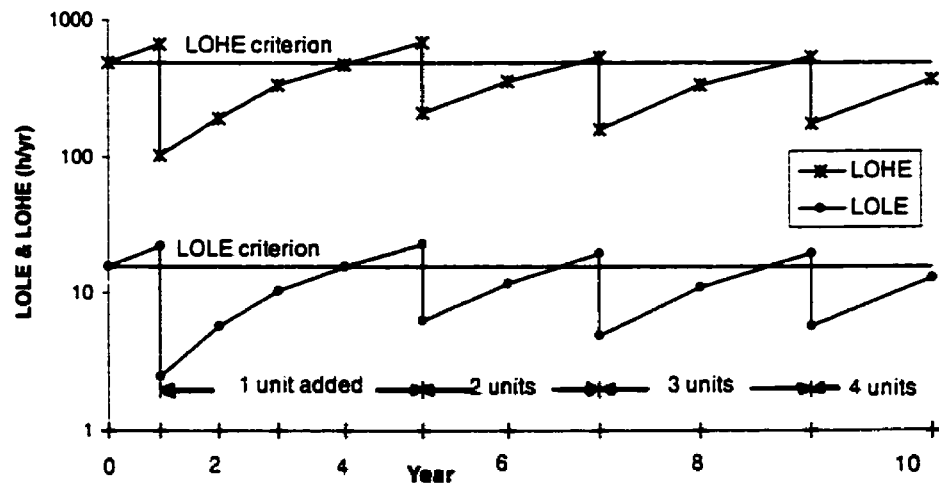


Figure 7.2: Adding Diesel Units to Maintain Reliability

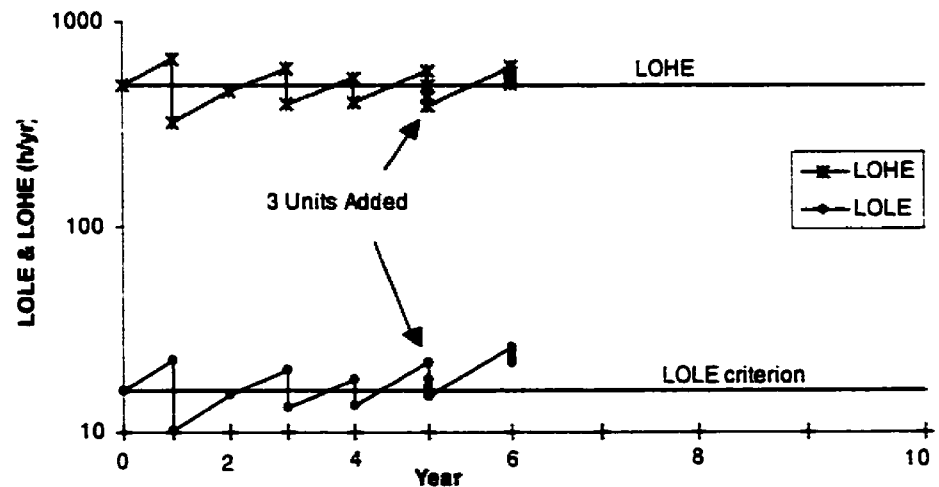


Figure 7.3: Adding WTG Units to Maintain Reliability

Figure 7.3 has been constructed with the assumption that the system load can utilize all the wind energy available at any instant. Practical constraints however limit the utilization of wind energy for system stability concerns. An operating constraint which limits the wind energy to 40% of the total energy consumption has been assumed in the study shown in Figure 7.4. This diagram illustrates the addition of WTG units to maintain the system risk within acceptable limits as the load increases in the example system.

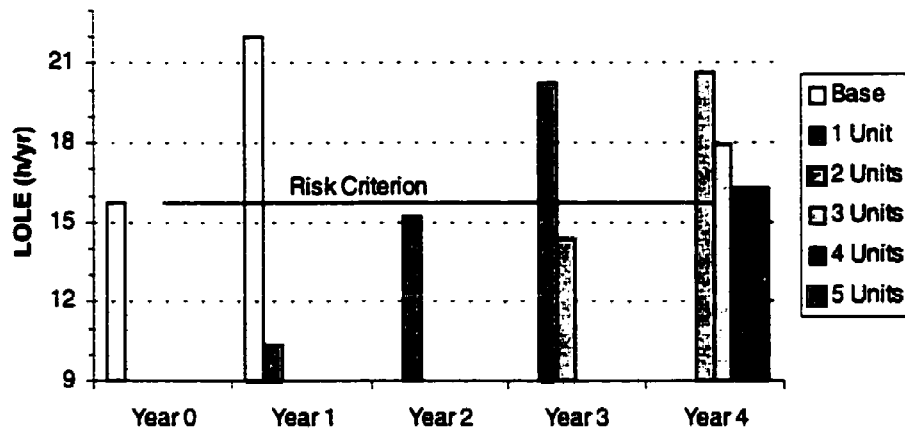


Figure 7.4: Adding WTG Units Considering an Operating Constraint

Figure 7.4 shows that the system risk can be maintained below the risk criterion up to Year 3 by adding a WTG unit in Year 1 and Year 3. Violation of the risk criterion in Year 4 cannot be avoided by further addition of wind energy sources. Figure 7.4 shows that there is no further decrease in system risk by adding 4 or more units in the system. In the given situation, the system reliability can only be maintained until Year 3 with the addition of WTG units alone.

Figure 7.5 illustrates the addition of PV arrays to the example system to meet the load growth. A set of 50 arrays is installed as a unit to expand the generating capacity in increments of 40 kWp. It can be seen that the system reliability cannot be maintained

above the risk criterion of LOLE = 15.73 h/yr by further addition of PV arrays after Year 2.

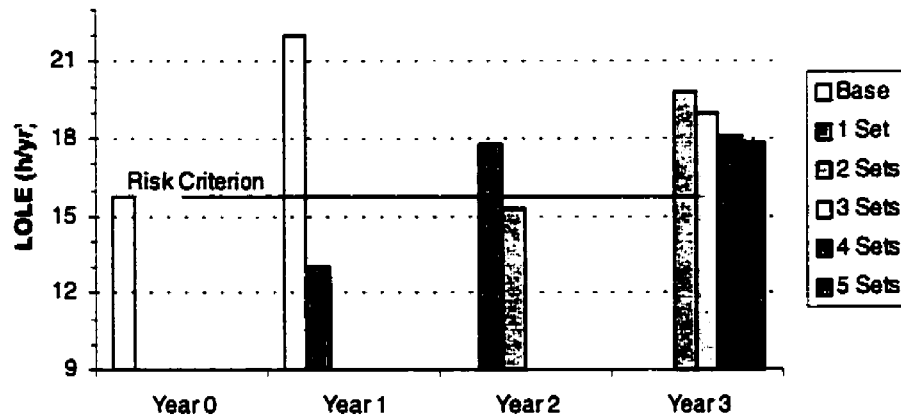


Figure 7.5: Adding PV Array Sets to Maintain Reliability

The study results in the Figures 7.3 – 7.5 clearly illustrate that the system reliability cannot be maintained at the desired level over a future period of time by the addition of renewable energy sources alone. The absence of PV energy during the nighttime always involves a certain level of system risk no matter how many PV arrays are added to the system. The addition of only WTG units cannot maintain the system adequacy as required due to three major factors; the intermittent nature of the wind energy, the exposure of all the installed WTG units to the same wind characteristics, and the operating constraints that limit the wind energy to a certain fraction of the diesel energy dispatch. Conventional units must therefore be installed in addition to the renewable energy sources at the appropriate times to maintain the system reliability at the acceptable level.

The conventional units would be the preferred choice in capacity expansion if system reliability were the only concern. An equally important concern is, however, to minimize the system costs. The addition of renewable energy sources offsets the costly fuel that

would otherwise be consumed by the diesel generating units. Figure 7.6 compares the fuel consumed when the three energy sources are added separately to the example system to maintain the system reliability at the acceptable risk and health criteria in Years 1, 2 and 3. The operating constraint of limiting the wind energy within 40% of the total energy consumption has been applied in evaluating the fuel offset by the WTG units. The total fuel consumption in the three years is also compared for the three different types of unit addition.

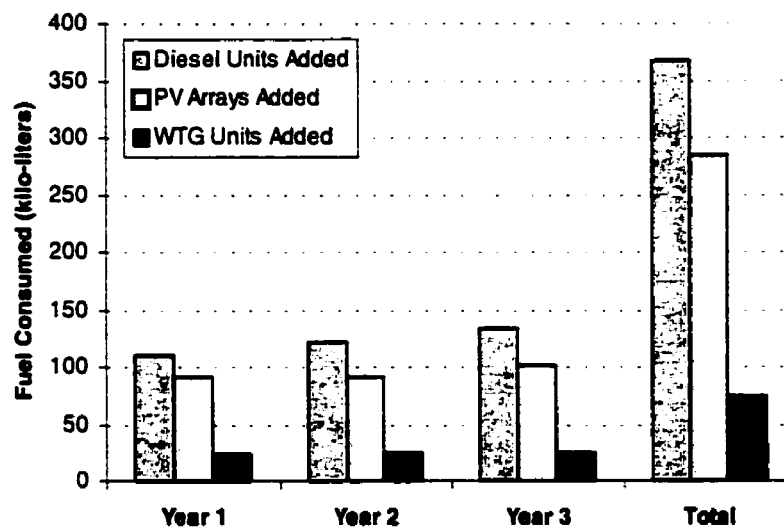


Figure 7.6: Fuel Consumed with Different Types of Energy Installations

It can be seen in Figure 7.6 that the volume of fuel consumed in the three years is 29% more when the diesel units are installed instead of the PV arrays. The installation of WTG units saves 80% of the fuel that would have been consumed if the diesel units were installed. The fuel cost savings must be compared with the associated installation and operating costs when deciding which energy sources should be installed at a certain point in time.

The best energy source choice for an expansion depends on the existing generating system configuration, the penetration levels of the renewable sources, and how closely the available renewable energy can follow the load variations. Section 5.4 notes that the amount of benefit in fuel savings obtained by adding renewable energy to a system decreases as the penetration levels increase above a certain limit. The addition of a renewable energy source, which already exists at a relatively high penetration level in a system, will not be beneficial since more of the installed energy will be wasted. A higher penetration level can be used with significant benefit if the renewable energy characteristic closely follows the load variation pattern.

The UER is the ratio of the available renewable energy wasted to the energy consumed and can be used as a criterion to decide whether a certain type of renewable energy source can be installed to provide desirable cost benefits. Figure 7.7 compares the UER index in Years 1, 2 and 3 when PV and wind energy sources are added separately to the example system to maintain the system reliability at the acceptable risk and health criteria. The chart considers the addition of 5 sets of PV arrays in Year 3, which is the only case that violates the accepted adequacy criteria in the Figure 7.7.

The appropriate value of the UER criterion for adding a particular renewable energy source in a system should be decided from an analysis of the cost benefits that depend on the fixed and variable costs associated with the energy addition, such as the unit installation, maintenance and fuel costs. The acceptable UER value for a PV addition will be lower than that for the wind energy because of the relatively high installation costs. The UER criterion for both PV and wind energy should be increased if the price of diesel fuel rises. It can be seen from Figure 7.7 that given a wind energy UER criterion of 20%, WTG units should not be added in Year 3 when the 40% operating constraint is applied. More WTG units can, however, be installed for higher benefits if no operating constraint is required.

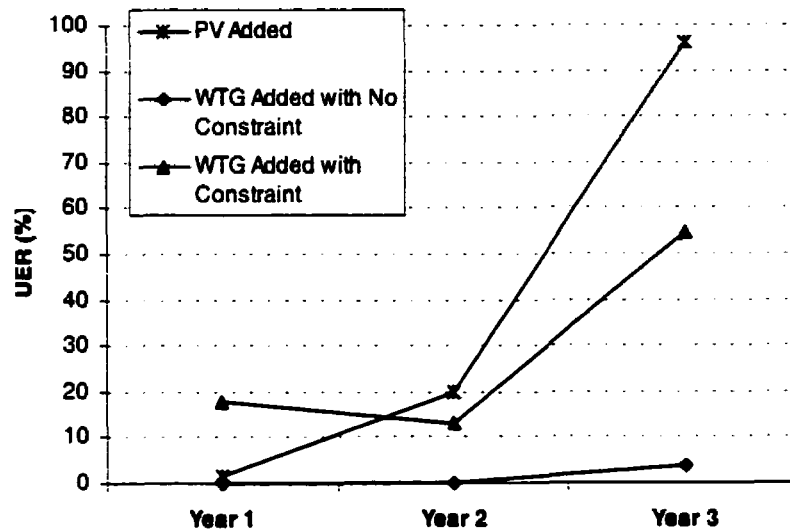


Figure 7.7: Comparing UER for PV and WTG Additions

Both the reliability and cost aspects must be considered when deciding the energy sources to add to a composite SIPS. Renewable energy sources can be installed at the proper times to lower the operating costs of the system. Long term planning is required, however, to obtain optimum benefits. The decision to install renewable energy sources in the future should also consider the trend of increasing diesel fuel prices, decreasing PV prices and increases in benefits obtained from continuous development in the wind and PV technology. The selection of renewable energy sources will also be influenced by government policies and financial incentives. Diesel units will have to be added at appropriate times when the costs of adding renewable energy sources is not justified by the benefits, and when the addition of renewable sources alone cannot provide acceptable levels of reliability.

7.5 Optimum Scheme Selection

The generating capacity of a composite SIPS can be expanded in many different ways to meet the anticipated load growth. A major problem in capacity planning is to determine the optimum expansion scheme that provides a reasonable level of system reliability at the minimum cost.

The discussions in Sections 7.3 and 7.4 provide useful guidelines that can be used to estimate the required energy generating sources and their installation dates in a series of potentially beneficial expansion options. The cost and worth of the selected schemes must be compared over the load forecast period to determine the optimum expansion scheme.

The expansion of the example system (Table 7.1) to meet the load growth (Table 7.2) for a period of ten years has been considered using five different schemes. The specifications of the energy generating sources added in the different expansion schemes are given in Table 7.4. The five example schemes which include the addition of diesel units, WTG units, PV arrays and a combination of these generating sources are shown in Table 7.8. The utilization of wind energy is constrained to supply no more than 40% of the total load in all the expansion schemes. The variation in the system risk and health as a result of unit additions and load growth with time is shown in Figure 7.2 for Scheme 0.

The system reliability has been maintained at the acceptable risk and health criteria ($LOLE = 15.73$ h/yr and $LOHE = 484.68$ h/yr respectively) in all five expansion schemes. The total cost during the period of ten years is calculated for each scheme and compared to determine the optimum expansion plan. The data given in Table 7.5 were used to evaluate the system costs.

It has been assumed that prices remain the same over the ten year period. The total costs of the five alternatives have been compared in terms of their present worth. An interest

rate of 10% has been assumed in the analysis. Table 7.9 illustrates the calculation of the present value of the total cost of the capacity expansion in Scheme 5.

Table 7.8: Different Capacity Expansion Schemes

Year	0	1	2	3	4	5	6	7	8	9	10
Scheme 0	B	D				D		D		D	
Scheme 1	B	W		D			W	D		D	
Scheme 2	B	WW			D			D		D	
Scheme 3	B	W		WD				WD		D	
Scheme 4	B	P	D			P	D		D		D
Scheme 5	B	P	W		W	D		P	D		D

B = Base example system

D = 1-20 kW diesel unit added

W = 1-40 kW WTG unit added

P = 1 set of 50 PV arrays added

Table 7.9: Present Value Calculation of the Total Cost for Scheme 5

Year	Used Fuel Energy (kWh)	Cost (\$)					Present Value (\$)
		Fuel	Unit Maintenance		Installation	Yearly Sum	
			diesel	WTG			
0	321914	70418.688	6438.28	0	0	76856.9675	76856.9675
1	294639	64452.281	5892.78	0	198000	268345.061	243950.056
2	262315	57381.406	5246.3	900	31200	94727.7063	78287.3605
3	295745	64694.219	5914.9	900	0	71509.1188	53725.8593
4	303152	66314.5	6063.04	1800	23400	97577.54	66646.7728
5	342709	74967.594	6854.18	1800	4500	88121.7738	54716.6883
6	387549	84776.344	7750.98	1800	0	94327.3238	53245.3151
7	395749	86570.094	7914.98	1800	66000	162285.074	83277.9031
8	449884	98412.125	8997.68	1800	1800	111009.805	51786.8933
9	510144	111594	10202.9	1800	0	123596.88	52417.1424
10	577115	126243.91	11542.3	1800	0	139586.206	53816.5251
Total:							868727.483

The figures in the second column of Table 7.9 were obtained from SIPSREL+ and are the expected energies supplied by the diesel generating units. A heat rate of 3.2 kWh/liter has

been used to calculate the fuel consumed in liters, which have then been multiplied by a fuel price of \$0.70 per liter to obtain the fuel costs shown in the third column. The maintenance costs for the diesel units in the fourth column are obtained by multiplying the diesel energy consumed in the second column by a rate of \$0.02/kWh. The yearly maintenance cost for the WTG units is obtained by multiplying the installed WTG capacity by a rate of \$22.50/kW. The total installed capacity of wind energy is 40 kW in Years 2 and 3 and 80 kW after Year 4. The installation cost in the sixth column includes both the unit cost and the cost of installation given in Table 7.5. An effective life of 20 years has been assumed with a salvage value of zero at the end of the plant life. A straight-line depreciation method has been used to calculate the resale value at the end of Year 10. The installation costs shown in the sixth column of Table 7.9 are the purchase price at the year of installation less the resale value at the end of Year 10. The figures in the seventh column are the sum of the values in the four preceding columns. The last column shows the present value of the annual costs in the seventh column obtained using Equation (7.1):

$$\text{Present Value} = \frac{F}{(1+i)^n} \quad (7.1)$$

where, F = future value
i = interest rate
n = number of years.

The present values of the total costs incurred in the ten year planning period for the five different capacity expansion alternatives are compared in Figure 7.8. It can be seen that Scheme 3 is the best expansion sequence that provides the acceptable level of reliability at the minimum system cost. Additional alternate schemes can also be compared to determine the optimum SIPS generating capacity expansion to meet the forecast load growth.

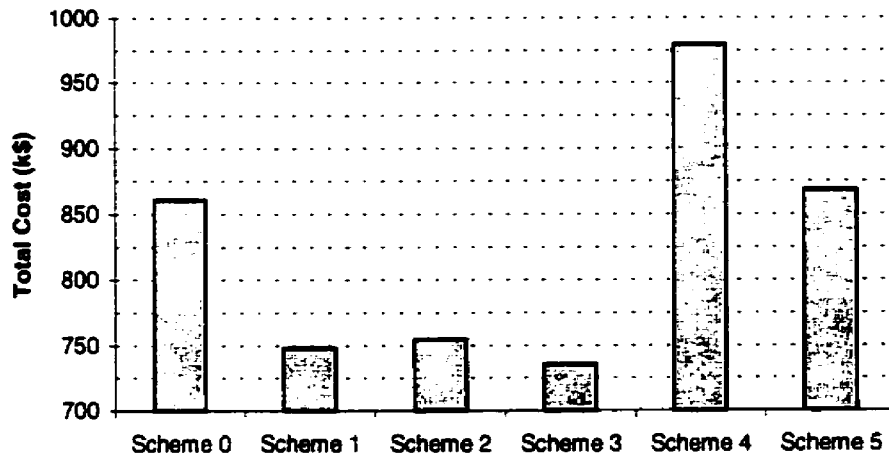


Figure 7.8: Present Value of the Total Cost for the Example Expansion Schemes

A simple example has been used to illustrate the procedure for determining the optimum capacity expansion of a composite SIPS. The effects of additional factors should be considered in actual capacity planning. Figure 7.8 shows that the costs associated with the expansion schemes that include PV energy are relatively high. This is due to the high capital costs of PV modules. The evaluation should also include government subsidies if available. Planning should also recognize possible future facility price trends. The rising price of diesel fuel and the falling price of PV modules should be predicted for the planning period using appropriate forecasting techniques. Additional factors such as variable project costs, inflation and interest rates also vary with time and must be incorporated in actual capacity planning.

7.6 Sensitivity Studies

The optimum expansion plan for a composite SIPS involves adding the appropriate energy sources at the right times to provide an acceptable level of system reliability at

minimum cost. The determination of the costs related to a particular expansion scheme is influenced by many different factors. It is important to analyze the effects of these various factors on the selection of the optimum scheme in the capacity planning process.

The price of diesel fuel varies with time and location. The price is relatively high at remote locations due to high transportation and storage costs. Many power utilities have to depend on the oil producing countries for imported fuel. The relative changes in supply and demand result in varying fuel prices. The dwindling nature of oil reserves has and will cause a rising trend in diesel fuel prices with time. Figure 7.9 compares the variation of the total costs in the five expansion schemes described in Table 7.8 with changes in fuel price.

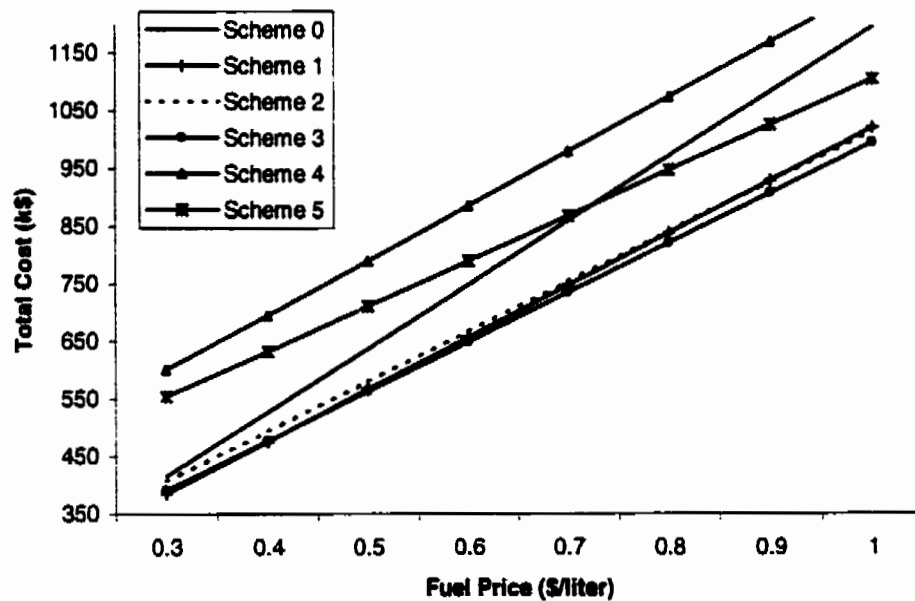


Figure 7.9: Total Costs at Different Fuel Prices

Figure 7.9 illustrates that Scheme 1 is the best if the price of diesel fuel is between \$0.30 - 0.40 per liter. Scheme 3 is the optimum expansion for diesel fuel prices in the range of

\$0.40 – 1.00 per liter. It can be seen from the Figure 7.9 that Scheme 0, which adds only diesel units, has the largest slope and is the most sensitive to the variation in fuel price. On the other hand, Scheme 5 adds all the three types of energy sources and is the least sensitive to the changes in diesel fuel price. Scheme 5 is a better choice than Scheme 0 when the price of diesel fuel exceeds \$0.74 per liter. Figure 7.9 also shows the amount of additional investment that will be required when the fuel price increases. It should be noted that a rise from \$0.70 to \$0.80 per liter will require an additional \$86362 in Scheme 3.

There are significant benefits from both the reliability and cost aspects if the system stability can be maintained without imposing an operating constraint on the use of the wind energy. Figure 7.10 compares Figure 7.8 to the case when the operating constraint is not considered.

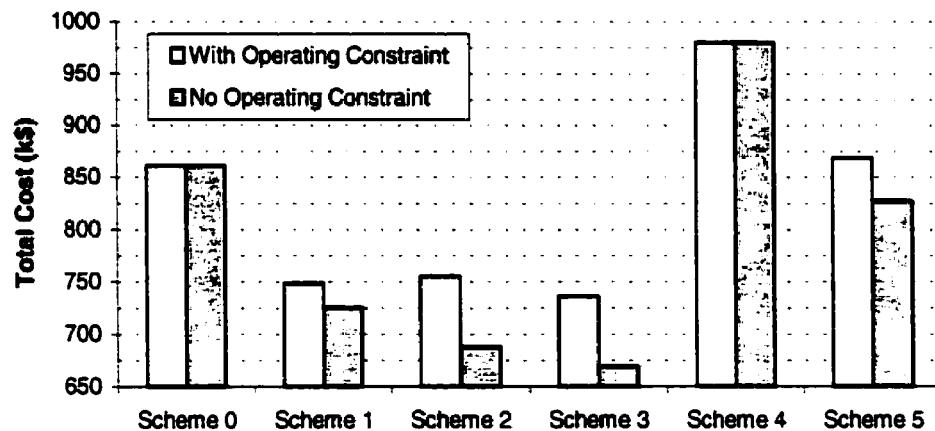


Figure 7.10: Impact of Operating Constraint on the Total Costs

Figure 7.10 illustrates that there is a significant decrease in the total costs of the expansion schemes that add wind energy when the operating constraints are not applied. The total cost of Scheme 3 is reduced by \$66867. The decrease in the total cost can be

compared with the cost of installing additional electronic components that support system stability without having to impose the operating constraint on the use of wind energy. The capital unit and installation cost of the WTG has been increased by 20% to incorporate the additional electronic components, and the total costs for the planning period are compared for the different expansion schemes in Figure 7.11.

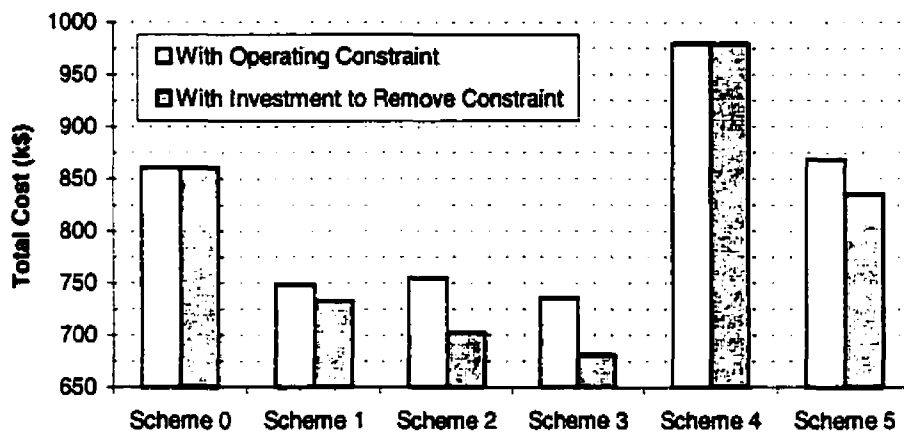


Figure 7.11: Comparing Total Costs with Additional Investment for System Stability

Figure 7.11 illustrates that there are significant benefits in making additional investments for system stability reasons. These benefits are site specific and therefore these studies should be done in each system with actual data in order to obtain a realistic evaluation of the actual benefits.

The weather characteristics at the site location largely influence the results of composite SIPS capacity planning studies. It has been assumed that the example system is located at a site in Swift Current where weather data from Environment Canada is available. Figure 7.12 compares the total costs in a new location where the atmospheric conditions are represented by the monthly solar radiation data from Toronto and hourly wind data from Saskatoon.

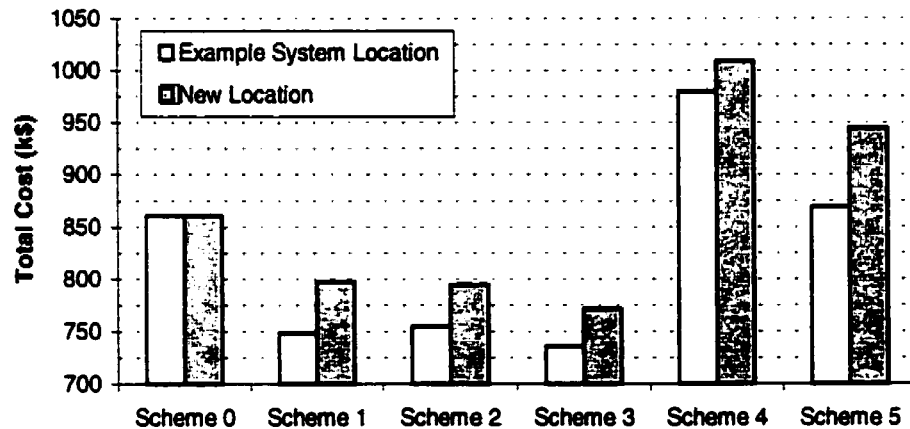


Figure 7.12: Impact of Site Dependent Weather Characteristics on the Total Costs

Figure 7.12 illustrates that there are significant increases in the total costs of the schemes that use solar or wind energy sources when the example system is considered in the new location. The system reliability also degrades to unacceptable levels in Schemes 1, 2, 3 and 5. Figure 7.13 illustrates the system health and risk levels with Scheme 1 at the new location.

Figure 7.13 shows that the accepted adequacy criteria (LOLE of 15.73 h/yr and LOHE of 484.68 h/yr) are violated in Years 1, 2, 5, 6, 8 and 10. The capacity expansion schemes devised for a particular location cannot be applied to similar systems at other geographic sites when renewable energy sources are considered. The system expansion conducted to maintain a consistent level of reliability is strongly influenced by the weather characteristics. These parameters vary considerably from one geographic location to another. The costs associated with the expansion of similar systems will also differ considerably under these conditions at different geographic sites.

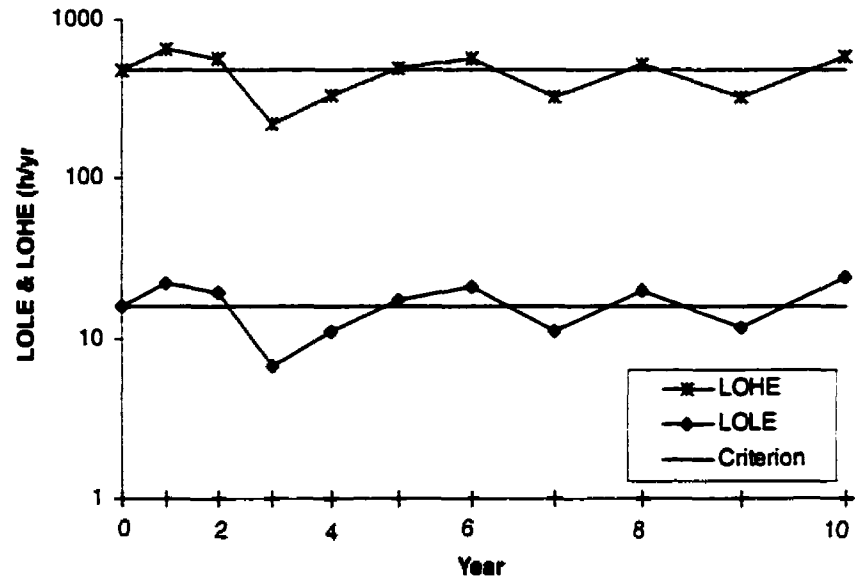


Figure 7.13: System Reliability at the New Location for Expansion Scheme 1

7.7 Conclusion

The generating capacity of a power system must be expanded to maintain an acceptable level of system reliability as energy demands increase with time. The installation of different proportions and combinations of conventional and unconventional energy sources are viable options in a composite SIPS. The major difficulty in capacity planning is to determine the optimum expansion scheme from very large number of possible options.

The determination of the optimum capacity expansion plan requires a comparative study of a number of alternative schemes. The discussion of the results from the studies described in this chapter provides useful guidelines in selecting potentially beneficial expansion schemes for a composite SIPS. The costs and worth of the selected schemes should be compared over the normal planning time horizon.

The determination of the appropriate dates for adding unconventional generating units in a SIPS is governed by different factors than for adding conventional energy sources. The objective of adding conventional units to a system is to meet the load requirements and maintain the system reliability. On the other hand, the addition of unconventional energy sources can provide lower operation costs in addition to assisting in meeting the system load and maintaining the system reliability.

The conventional units are much superior to the renewable energy sources in providing system reliability. A desired level of reliability can always be obtained in a composite SIPS by adding appropriate diesel generating units at the proper times. It is usually beneficial to postpone the installation of a diesel unit whenever possible since the present value of money is less when an investment is made at a later date. The conventional units should be added to the system just in time to avoid violation of the accepted reliability criterion. A composite SIPS generation expansion scheme can include different types of energy sources. Diesel units should be considered when the costs of adding renewable energy sources are not justified by the benefits and when the addition of unconventional sources alone cannot provide the required level of system reliability.

The installation of unconventional energy sources to expand a composite SIPS provides a relatively lower reliability benefit than the addition of conventional generating units. The studies show that the desired level of system reliability cannot always be obtained by adding renewable energy sources. The addition of PV or wind energy sources must be accompanied by diesel units at the appropriate times to maintain the system reliability at the acceptable level. The addition of renewable energy sources, however, offsets costly fuel that would otherwise be consumed by the diesel generating units and significantly lowers the system operating costs. The savings in the fuel costs must be compared with the cost of installing adequate capacity to maintain acceptable reliability plus other associated costs of operation and maintenance in deciding which types of energy sources are to be installed at a certain point in time.

The decision to install a certain type of renewable energy source should consider the configuration of the existing generating system, the penetration level of that energy source, and how closely the available renewable energy will follow the load variations. The UER can be used as a criterion to decide whether a certain type of renewable energy source can be installed to provide acceptable cost benefits. The UER criterion for a particular renewable energy source can be determined by analyzing the installation, maintenance and fuel costs.

A UER value associated with the addition of a renewable energy source in excess of the UER criterion indicates that this investment will waste considerable available energy. A relatively low UER value indicates potential benefits in adding more of that particular energy source. The appropriate type of unconventional energy should be added whenever cost benefits can be obtained regardless of the fact that the system reliability may be relatively high at that time. The earlier the installation of renewable energy sources, the higher will be the savings in the fuel cost. The decision to install renewable energy sources in the future must also consider the trends in increasing diesel fuel prices, decreasing PV prices and the increases in benefits that can be obtained from the continuous development in the wind and PV technology. Government policies and available financial incentives should also be considered in the installation of renewable energy sources in a composite SIPS.

The generation expansion of a composite SIPS must consider both the reliability and cost aspects. Long term planning must be done to determine the optimum benefits. The optimum expansion plan for a composite SIPS consists of adding the appropriate energy sources at the right times to provide an acceptable level of system reliability at the minimum cost.

The effects of many different factors must be considered in actual capacity planning of composite SIPS. Studies have been conducted to analyze the effects of varying diesel fuel prices, changing geographic system locations and imposing and removing operating

system stability constraints. The price of diesel fuel varies with time and location. The total cost increases with rising fuel prices when more diesel units are added to the system. The weather characteristics that dictate the amount of energy from a renewable source vary with the geographic location. The reliability and cost associated with the expansion of similar systems can vary significantly at different geographic sites. The reliability and cost benefits will increase significantly if the stability of the system can be maintained without imposing operating constraints on the use of the wind energy. The cost benefits can be compared with required investments in additional electronic components to maintain system stability without restricting the use of wind energy.

The discussions in this chapter provide useful indicators regarding appropriate dates, types of energy sources and their penetration levels in the formulation of potentially beneficial capacity expansion schemes for composite SIPS. The selection of an optimum expansion plan has been illustrated with an example. The effects of price changes, operating constraints and geographic site changes are also illustrated. Additional factors that can influence capacity planning decisions are also discussed. The material presented in this chapter should help system planners to decide on appropriate installation sites, the types and mix of different energy generating sources, the optimum operating policies for system stability, and the optimum generation expansion plan to meet the increasing demand in a composite SIPS.

8. SUMMARY AND CONCLUSIONS

The rapid growth of photovoltaics and wind energy applications and their immense potential for future use dictates the need to seriously consider the quality of power supply that can be obtained and the associated cost/benefits that can be achieved. The application of these renewable energy sources to SIPS has received considerable attention throughout the world due to the potential benefits from replacing costly diesel fuel that drive the majority of conventional SIPS. This thesis describes the development of appropriate techniques and tools to provide realistic reliability and cost evaluation of composite SIPS.

The application of reliability evaluation techniques varies widely in practice and depends largely on the type of power system. The historical development of reliability methods in large interconnected systems has seen a gradual shift from deterministic to probabilistic techniques. The existing probabilistic techniques have not been considered applicable to SIPS. Most SIPS use the conventional deterministic approaches to determine system capacity requirements. The problem with these methods is that they cannot recognize the random behaviors inherent in a power system.

System well-being analysis creates a bridge between the deterministic and probabilistic methods and defines indices that are useful in practical adequacy assessment of SIPS. A specified deterministic criterion, such as the LLU, can be used to drive the probabilistic assessment of system health, margin and risk. The well-being indices can be obtained using either a direct analytical approach or a simulation technique. Considerable development work has been done in this area [6, 29, 30, 31, 32, 33, 34].

A Monte Carlo simulation approach has been used in this research to develop a reliability evaluation model for composite SIPS. This method is very useful when the system under study becomes too complex for analytical techniques. MCS is a practical approach to evaluate the effects of including renewable energy sources in SIPS, due to the inherent complexities of modeling the random weather variables, modeling the energy conversion process, and conducting corresponding adequacy evaluation.

The developed overall composite SIPS evaluation model integrates three separate simulation models. The first simulation model generates synthetic data for each hourly atmospheric condition. The second model evaluates the chronological hourly power output by the renewable energy sources. The outcomes of the first two models are similar for both the PV and wind energy sources. The third model combines all the conventional and non-conventional sources and simulates the overall system to obtain the desired reliability and cost indices.

The developed models designed to conduct different functions within the evaluation process have been linked together in an integrated framework and implemented in a software tool named SIPSREL+. This software tool can generate risk indices, well-being indices and additional energy based indices to provide realistic measures of renewable energy utilization in composite SIPS. SIPSREL+ can be used to conduct a wide range of studies related to system adequacy and cost in order to analyze the actual benefits obtained from renewable energy sources.

The MCS model in SIPSREL+ requires considerable computation time. Excessive computation is avoided by terminating the simulation process when it reaches acceptable convergence. The convergence criteria must produce results with acceptable accuracy. Studies on a number of different systems using various seeds show that accuracy can be achieved within 3% deviation from the mean results in most cases when a simulation involves at least 4000 yearly samples. The convergence of the simulation process requires

more samples for small systems with high reliability and high renewable energy penetration.

Composite SIPS reliability and economics are affected by the many different variables that influence the behavior of the system. The studies described in this thesis compare the effects on the system indices of energy system composition, energy source FOR, load levels, operating constraints and geographic system location.

The reliability degrades in terms of both system risk and health with increase in system load in all types of composite SIPS. The relative decrease in system reliability is, however, different when different types of energy source are included in the system. Renewable energy sources will offset more fuel as the load increases if the system has significant expected surplus energy prior to load growth.

The composite SIPS reliability can be increased by installing additional conventional and/or renewable energy sources. The reliability benefits obtained from the addition of conventional diesel generators are much greater than those obtained by an equal capacity addition of PV arrays or WTG units. The relatively high reliability achieved by the diesel units is also accompanied by increased operating costs due to fuel consumption. The reliability benefits and fuel savings from adding PV and WTG units depend on the site-specific weather data. The addition of renewable energy sources can be increased to improve reliability and replace diesel fuel only up to a certain point, after which no further benefit can be obtained. The major benefit of adding renewable energy to SIPS is the reduction in the system operating costs.

The level of reliability provided by a composite SIPS and the economic benefits from the fuel offsets are largely dictated by the inherent atmospheric characteristics of the system geographic location. The system reliability and fuel offset increases when the mean wind speed at a WTG system location increases, and the mean solar radiation increases and the ambient temperature decreases at a PV system site. The effect of temperature is,

however, noticeable only at locations with high solar radiation. The benefits increase when the time varying renewable energy availability more closely follows the chronological load variation.

Wind energy is generally a better choice than PV from both reliability and economic considerations. The benefits from wind energy sources, however, can be limited significantly by the operating constraints imposed to maintain system stability by restricting the amount of wind energy that can be supplied to the load. The benefits from increased wind energy penetration will decrease when a more restrictive operating constraint is applied. The optimum mix of PV and wind energy sources can be evaluated from both reliability and costs aspects for a system with a given operating constraint.

Generating unit FOR are important parameters in power system reliability evaluation. An increase in the FOR of any conventional unit significantly degrades composite SIPS reliability. Reasonable variations in unconventional unit FOR, however, do not have considerable impact on the system risk or health. Significant investment in more reliable PV cells or WTG units does not significantly improve system reliability.

Composite SIPS reliability evaluation should be conducted using techniques and indices that best respond to the nature of the renewable energy sources. The existing deterministic methods applied to SIPS cannot be directly applied to a composite SIPS since the renewable source capacity is a random variable that rapidly fluctuates with time. The expected capacity of an unconventional unit can be estimated and depends on the site specific weather characteristics and the energy conversion parameters. The basic weakness of deterministic methods is that they cannot recognize the random behavior of a system. The utilization of a single probabilistic risk index, such the LOLE, has not been readily accepted in SIPS evaluation despite its routine application in large systems. The well-being indices provide probabilistic evaluation of the degree of comfort in satisfying a specified deterministic criterion. Both the system health and risk indices provide useful information but from different aspects of system reliability.

The system health indices respond differently than the risk indices depending on the different factors acting on a composite SIPS. The addition of a large conventional unit in a composite SIPS provides higher benefits in system health than system risk. A system risk criterion is more restrictive than the health criterion when adding relatively small generating units. The capacity distribution is more continuous for renewable energy sources and causes less distortion in the health and risk indices. The system may violate the health criterion if the risk criterion is used to drive capacity planning and vice-versa. The dual criteria method described in this thesis jointly uses both the health and risk criteria to ensure that the system is reliable from both aspects.

The generating capacity of a power system must be expanded over time to meet the future load growth at an acceptable level of system reliability. Composite SIPS expansion requires comparative cost and reliability analyses of a number of alternative schemes over the normal planning time horizon. The optimum expansion plan consists of adding the appropriate energy sources at the right times to provide an acceptable level of system reliability at the minimum cost.

Composite SIPS expansion can include different types of energy sources. Conventional units can provide higher reliability benefits than renewable energy sources. A desired level of system reliability cannot always be obtained by adding only renewable energy sources. The addition of PV or wind energy sources must be accompanied by diesel units at the appropriate times to maintain the system reliability at the acceptable level. The addition of renewable energy sources, however, offsets costly fuel and significantly lowers the system operating costs. The appropriate renewable energy should be added whenever acceptable cost benefits can be obtained regardless of the fact that the system reliability may be relatively high at that time. The earlier the installation of renewable energy sources, the higher will be the fuel cost savings. On the other hand, it is usually beneficial to postpone the installation of a diesel unit whenever possible since the present value of money is less when an investment is made at a later date. Diesel units should be considered when the cost of adding renewable energy sources is not justified by the benefits and when the

addition of unconventional sources alone cannot provide the required level of system reliability.

The selection a certain type or mix of renewable energy source should consider the configuration of the existing generating system, the penetration level of that energy source, and how closely the available renewable energy will follow the load variations. The UER index can be used as a criterion to decide whether a certain type of renewable energy source can be installed to provide acceptable benefits. A relatively low UER value indicates potential benefits in adding more of that particular energy source. The decision to install renewable energy sources in the future must also consider the trends in increasing fuel prices, decreasing PV prices and the increases in benefits that can be obtained from the continuous development in the wind and PV technology. Government policies and available financial incentives should also be considered in the installation of renewable energy sources in a composite SIPS.

Composite SIPS capacity planning should consider the effects of many different factors. The price of fuel varies with time and location. The total expansion cost increases with rising fuel prices when more diesel units are included. The reliability and cost associated with the expansion of similar systems can vary significantly at different geographic sites. The reliability and cost benefits will increase significantly if the stability of the system can be maintained without imposing operating constraints on the use of the wind energy. The additional investment in electronic components to maintain system stability can be compared with the benefits from relaxing the restrictions in the use of wind energy.

The methodologies and the evaluation tools developed in this research work can be applied to conduct a wide range of reliability and cost analyses of composite SIPS. The concepts presented and the examples illustrated in this thesis should help system planners to decide on appropriate installation sites, the types and mix of different energy generating sources, the optimum operating policies, and the optimum generation expansion plans to meet the increasing load demand in composite SIPS.

APPENDIX A: OBJECT-ORIENTED DEVELOPMENT OF THE SOFTWARE TOOL

A1. Introduction

SIPSREL+ is a software tool that can be used to conduct a wide range of cost and reliability evaluation of composite SIPS. An object-oriented approach has been used to facilitate periodic modification and future extension of the software. A UML (Unified Modeling Language) tool called Rational Rose 98 was used to capture the requirements, analyze and design the system.

An object oriented development of a software includes incremental analysis, design, programming and testing in a loop process in multiple phases. Using this approach, the developed software tool can be further extended or modified in the future with relative ease. SIPSREL+ was developed in a cyclic process in many phases. This appendix only covers the first two development phases of the software building process. The tasks associated with each development phase are described in the following:

Phase 1: The first phase of development started with a simple electric power system containing only one type of energy source, the PV arrays. The PV sub-system generates electrical energy which depends on the weather data. The system analysis and design were modeled for this phase using Rational Rose 98 and the source codes were generated in FORTRAN and C++ programming languages. The results obtained from this phase were tested and analyzed.

Phase 2: A graphical user interface (GUI) for the Phase 1 application was developed in the second phase. The analysis, design and programming were done for the GUI and its interaction with the domain application. The source codes for the GUI were generated in Visual Basic. The application and the GUI developed at the end of this phase were tested together.

Other Phases: The third phase added wind energy sub-system to the existing PV system and repeated the first two development phases with the additional energy source. The next phase added diesel generating units to the power system. The sub-sequent phases included more complexities in the system, one step at a time in a cyclic process.

A2. Requirement Analysis

A major software development task is to capture the requirements for the desired application. The following requirement specification were identified for the system development:

1. The hourly weather data for the composite SIPS location is generated by other software applications.
2. The user has the hourly customer load data for the system in a sequential file.
3. The user specifies the generating system configuration.
4. The user provides the manufacturer's specification for the system components.
5. The user provides the performance data of the energy sources.
6. The generating units fail in random.
7. The failed units are repaired and brought into operation.
8. The weather dictates the energy output from the photovoltaic and wind units.
9. The user specifies the system operating constraints.

10. The total power generation is compared with the total customer demand in each hour for a year and the reliability and cost indices are calculated.
11. The power system is simulated for a large number of yearly samples until convergence is reached.
12. The user devises the convergence criteria by specifying the acceptable limits.
13. The user can view the results.

The necessary use-cases were identified based on the system requirements. A use-case diagram is shown in Figure A1 to capture the system requirements in terms of the identified use-cases. A few of the use-cases are described here.

- Use-Case ‘Configure System’

The user configures the generating system by specifying the sub-systems in it and the number of generating units in each sub-system. The user then provides the performance data and the manufacturer's specification for all the generating units in the power system.

- Use-Case ‘Do Simulation’

The user runs the simulation which involves generating a random number, which in turn controls the generating unit operating states (up state or failed state) in a sequence of events. This uses the use-cases ‘Check Hourly’ and ‘Check Convergence’. The simulation process repeats until convergence. After convergence, the output data is processed and stored in a permanent storage file.

- Use-Case ‘Check Convergence’

This use-case calculates the LOEE index each year, calculates the deviation from the last year and compares with the previous deviation values to check for convergence of the simulation process.

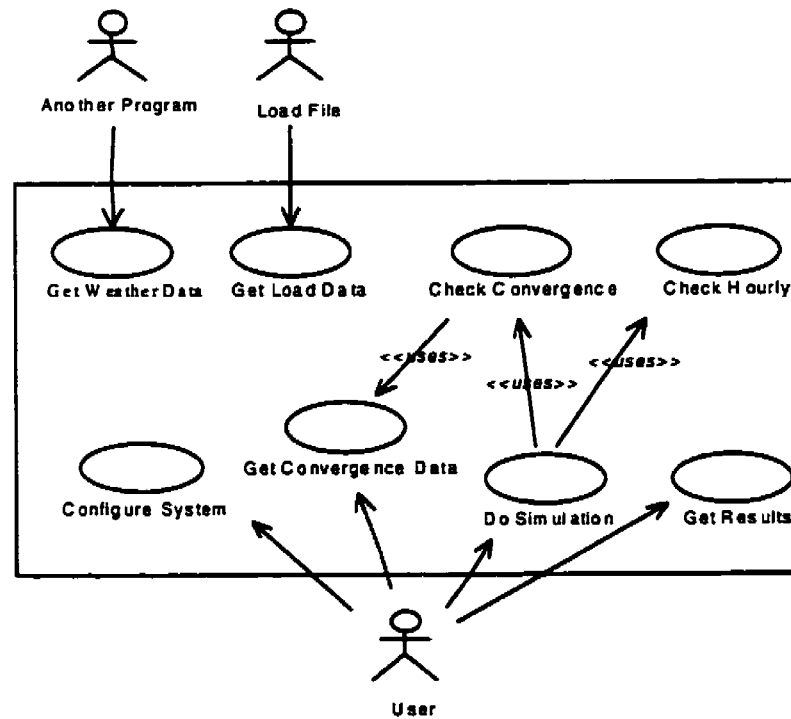


Figure A1: Use-case Diagram

A3. Domain Analysis

The domain analysis that follows the basic requirement analysis involves identifying the important concepts that must be handled and their relationships to each other. At this stage, the key classes required to simulate the PV sub-system were sketched without the details.

The domain class structure is shown in Figure A2. The figure illustrates the static relationships between the initially modeled key classes. Additional classes were identified and introduced in the model in later phases of the software development.

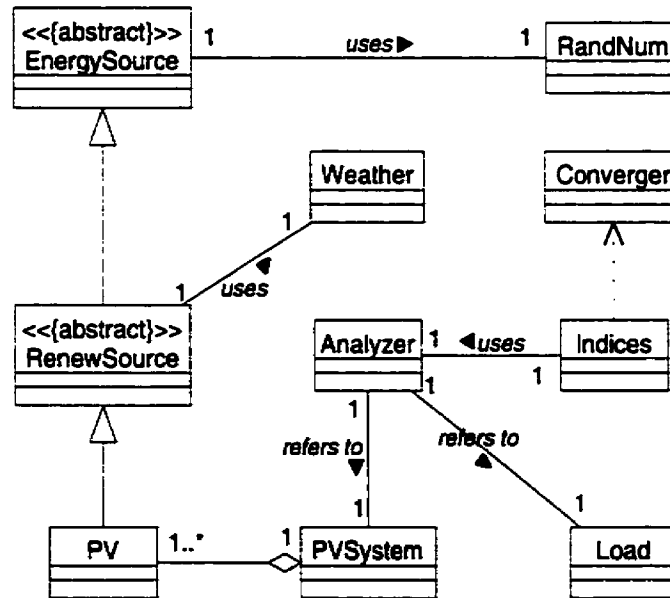


Figure A2: Domain Class Structure for Phase 1

A further analysis of the system at this phase was done to model the interactions between the classes with respect to the identified use-cases. Sequence Diagrams and Collaboration Diagrams illustrate the interaction between different objects in sequence of time and events respectively. The diagrams were constructed for all the use-cases. The sequence diagram for one such use-case, 'Configure System', is shown in Figure A3. Figure A4 shows the collaboration diagram for the use-case 'Do Simulation'.

Figure A3 illustrates the time sequence in configuring the generating system. The user provides the necessary data in the object windows in the presentation layer. These messages are synchronous, so that no other operations are conducted until the proper messages (error or success messages) are returned to the user. The data entered in the window objects are transferred to an interface object from which the data is passed into the domain layer and are received by the object 'PVSysyem'. This object creates multiple 'PV' objects, one for each PV array in the configured system.

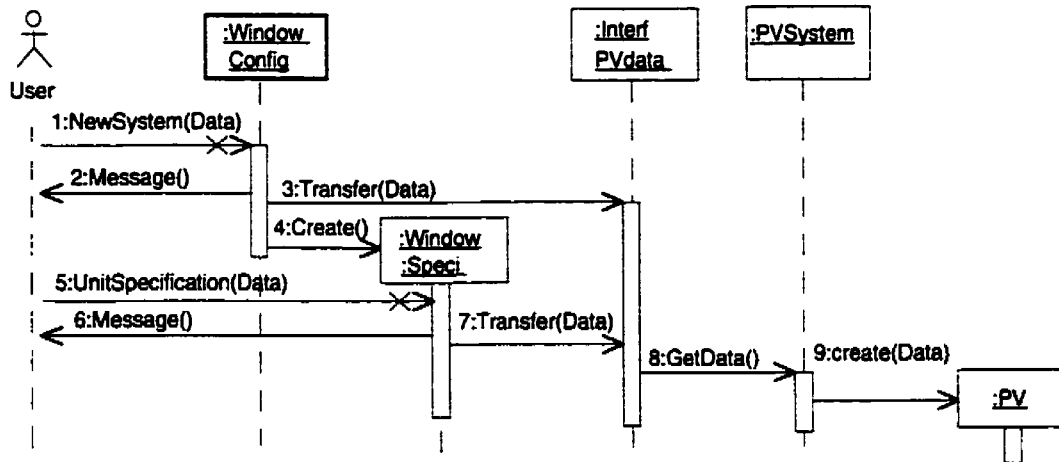


Fig. A3: Sequence Diagram for Use-Case 'Configure System'

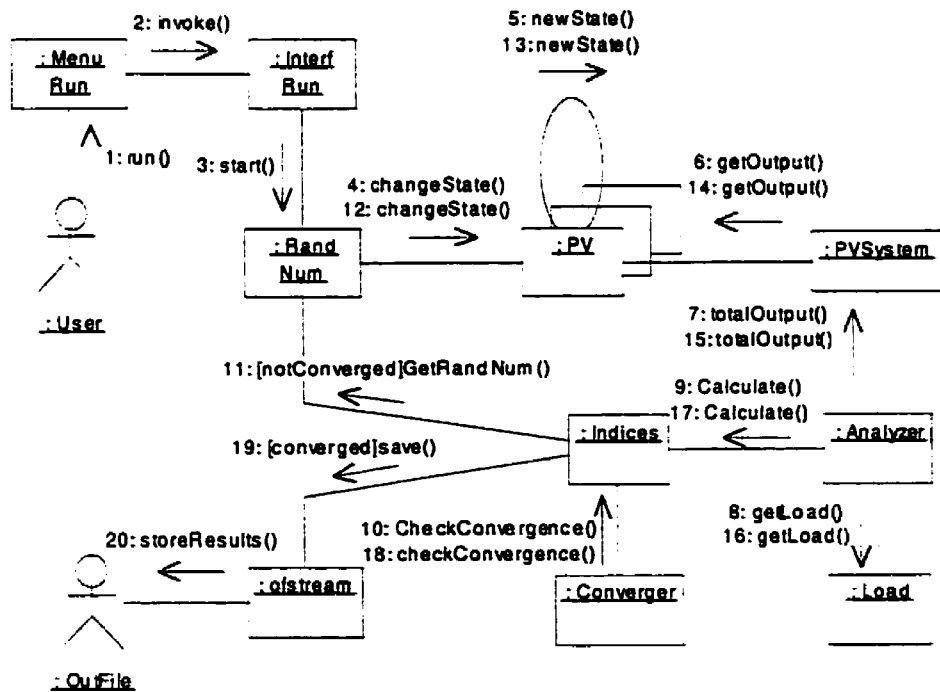


Figure A4: Collaboration Diagram for the Use-Case 'Do Simulation'

Figure 4 illustrates the interaction of the collaborating objects to perform the system simulation. The user clicks the 'Run Menu' sending a signal via an interfacing object to the domain layer. The random number generator generates a random number for each PV array to determine changes from the up state to the failed state and vice-versa. The object 'PVSystem' checks the operating state of each PV array contained in it and calculates the total power output. The object 'Analyzer' takes the total power output data from the object 'PVSystem', takes the system hourly load data from the object 'Load', calculates the LOEE to check for convergence by comparing with the specified criteria in the object 'Converger'. The simulation repeats until convergence. Upon convergence, the results are stored in a file object 'OutFile' via the file handling library class 'ofstream'.

A4. System Design

The analysis model is expanded in details by considering all the technical implications and restrictions during the design stage. The classes defined in the analysis were detailed and new classes were added to handle the system operations. The design began from a high-level architecture design and developed into finer granularity in a more detailed design. The architecture design, detailed design and the generation of source codes for the Phase I PV system are described.

A4.1 Architecture Design

The system was divided into a presentation layer, an application logic layer and a storage layer in a three-tier architecture design. The system was grouped into packages for handling specific functional areas. The domain application logic was separated from the technical logic that deals with user-interface and storage systems. The objects within the three layers communicated with each other via the interface objects of each layer. This

was done to make the system as loosely coupled as possible. The overall system was grouped into the following packages:

- **'User Interface' Package**

This package in the presentation layer included the classes responsible for creating a user friendly environment to enable the user to enter and view data. The classes were based on the Visual Basic tool for writing user-interface applications. This included menu and window objects, as well as, objects that interface with the domain layer.

- **'System Components' Package**

This package in the domain application layer included the classes for the different types of energy source, generating units, energy sub-systems, weather and customer load.

- **'System Operation' Package**

This package, also in the domain layer, included the classes responsible for simulating the dynamic behavior of the power system and evaluating the indices. It included the classes for the random number generator, converger, analyzer, system indices and for the objects that interface with the presentation and storage layers.

- **'Data Storage' Package**

This package, in the storage layer, included the C++ library classes for handling data files, such as creating disk space for storing data or locating and interpreting the data in the magnetic storage.

Figure A5 illustrates the interactions of the key classes within each package, between classes across two packages and across layers. At this point, only classes in the presentation layer package that interface with the domain layer are shown.

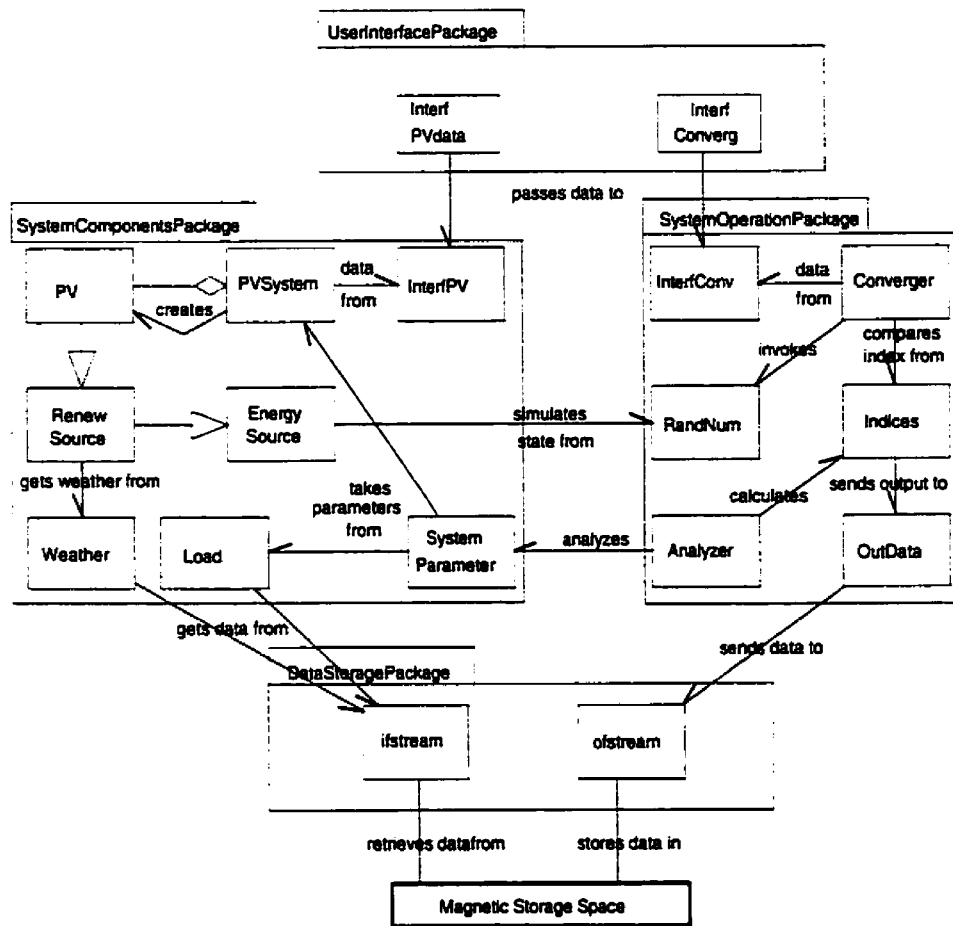


Figure A5: Package Diagram Showing Interaction Between Key Classes

A4.2 Detailed Design

The design proceeds from a high-level into the detailed descriptions of all the classes within each package. The attributes and operations of each class are realized at this stage. Standard software engineering concepts were applied to assign responsibilities to the identified classes.

The details of the 'System Component' package and the 'System Operation' package are shown in the class diagrams in Figure A6 and A7 respectively.

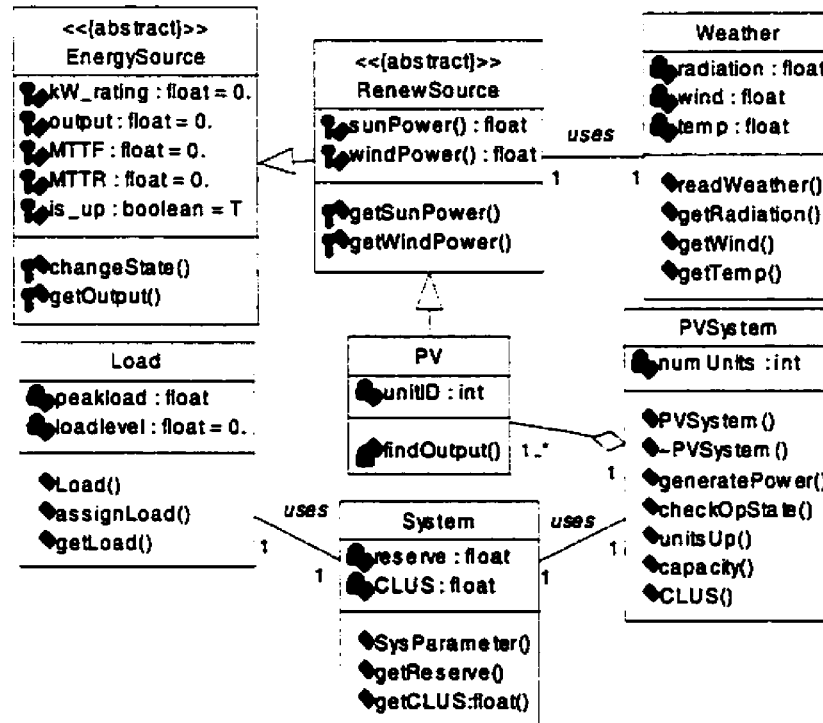


Figure A6: Class Diagram for the 'System Component' Package

An object of the class 'PVSys' in the class diagram in Figure A6 gets the user input data from a user interface object. It then creates the required number of 'PV' objects and assigns the values provided by the user. The 'Weather' object gets solar radiation, wind speed and temperature data from the storage layer. These data are used by the 'PV' objects to calculate the generated PV power. The operating state of each 'PV' object is determined by the corresponding random number obtained from the 'System Operation'

package. The 'PVSystem' object checks the state of each 'PV' object, finds the arrays that are in the up state, calculates the total power output, and sends the total power and the CLUS data to the 'System' object. The 'Load' object gets one load data from the storage layer at a time in a loop and sends it to the 'System' object which calculates the system capacity reserve. The capacity reserve and the CLUS data are then sent to the 'System Operation' package.

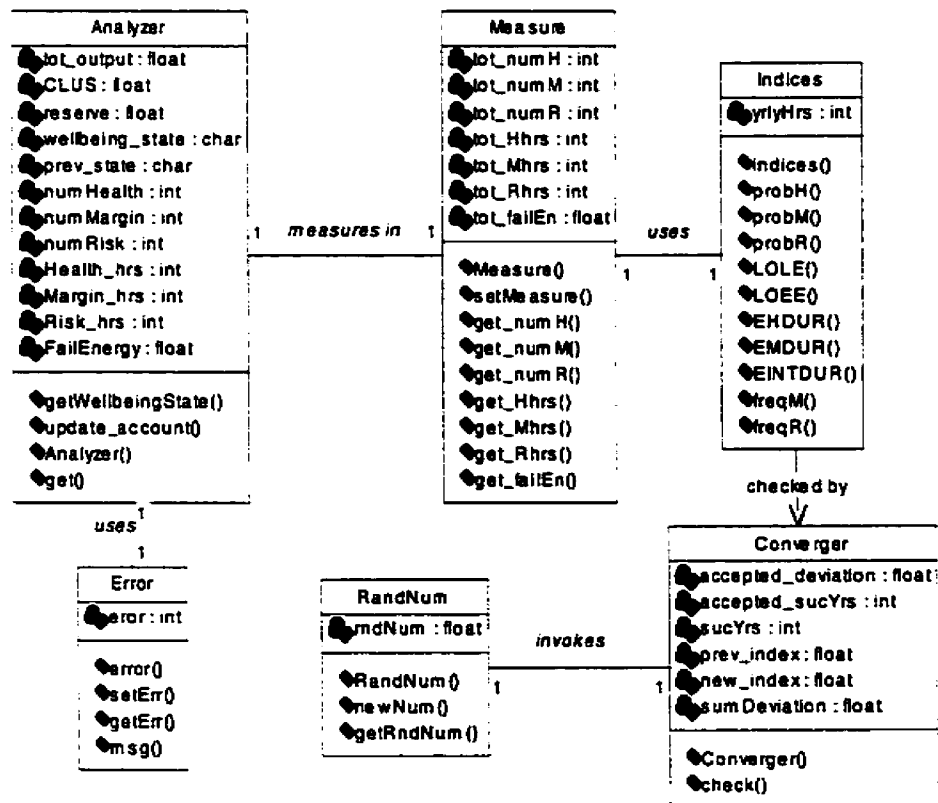


Figure A7: Class Diagram for Classes within System Operation Package

The class diagram in Figure A7 indicates that a user interface object gets the simulation convergence data from the user and passes them to the 'Converger'. This object invokes the object 'RandNum' that generates a random number between 0 and 1 for each 'PV' object in the 'System Component' package. The object 'Analyzer' gets the system capacity reserve and CLUS data from the 'System Component' package and analyzes the well-being state of the 'System' object. The object 'Measure' measures the different system parameters, which are used by the 'Indices' object to calculate the LOEE. The calculated LOEE is taken by the 'Converger' object to check for convergence. The simulation is converged if the convergence criteria are met. The 'Converger' will again invoke the 'RandNum' object if the convergence criteria are not met. After convergence, the 'Indices' object calculates the reliability and energy indices and sends them to the storage layer via the interfacing object 'OutData'.

A generating unit periodically transits from the available operating state to the failed state and vice-versa throughout the simulation process. The output power depends on the state of a unit at a particular time. The state diagram in Figure A8 models the operating states of a PV array.

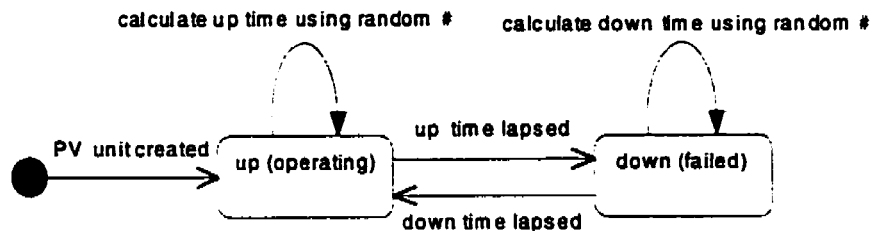


Figure A8: State Diagram of a 'PV' Object

The 'Analyzer' object analyzes the well-being state of the overall power system represented by the 'System' object. The system reserve is calculated and compared with the CLUS hourly to determine the system well-being state at that moment. Figure A9 illustrates the state diagram for the system.

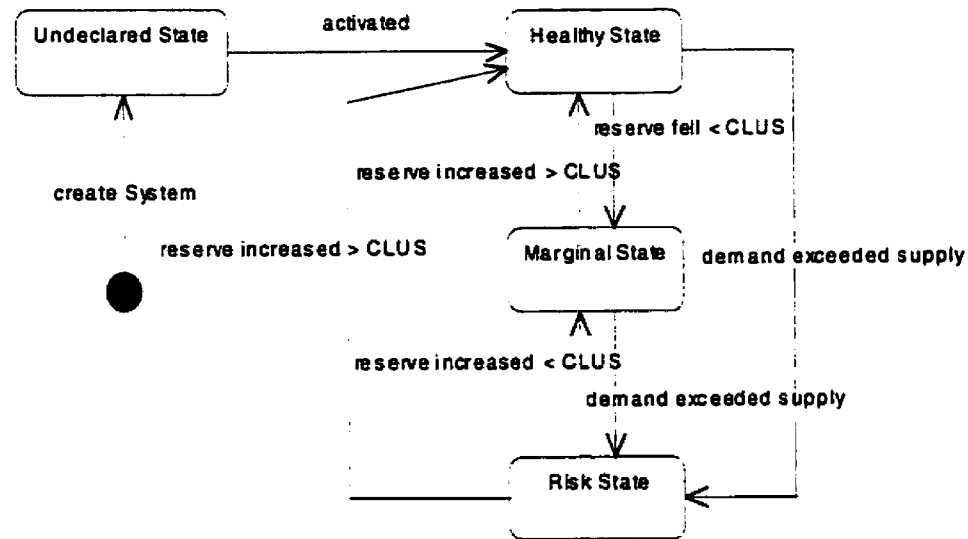


Figure A9: State Diagram for the Power System

A4.3 Source Codes

The source codes have been generated in FORTRAN and C++ programming languages. The system domain application and the user-interface were built separately. The source codes for driver program to initialize and drive the different class objects are in C++. The WATGEN program and the program to simulate the generation of electrical energy by a PV array are in FORTRAN language. These programs have been assigned as functions to the classes 'Weather' and 'PV' respectively.

A5. User-Interface Design

The second phase of the software development was to develop the user-interface for the PV system application. The interactions of classes within the 'User Interface' package are shown in the class diagram in Figure A10.

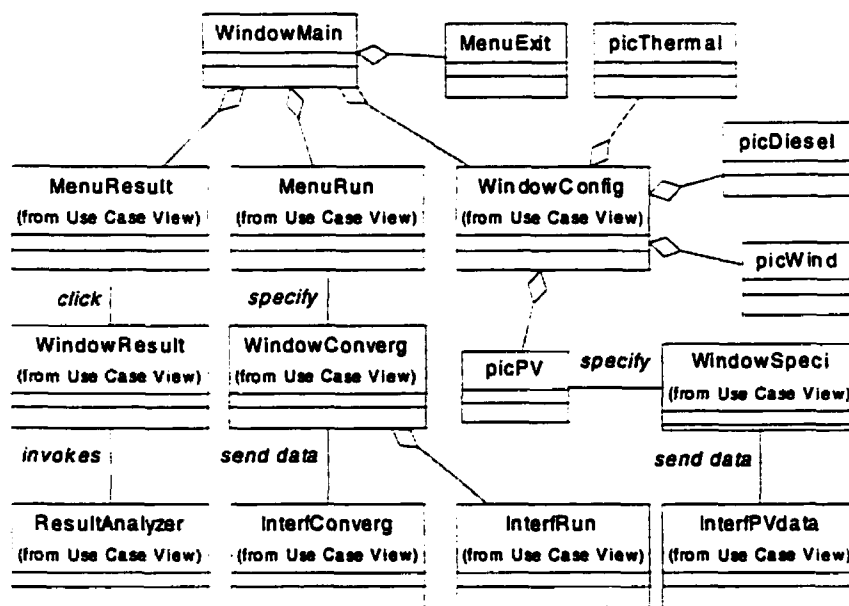


Figure A10: Class Diagram for 'User Interface' Package

The source codes for the GUI have been written Visual Basic. The necessary coupling between the domain application and the presentation layers were provided through interfacing data file objects that can be accessed independently by either application irrespective of the tools used to develop them.

A6. Analysis and Design in Subsequent Phases

The overall system application was built incrementally, starting from a smaller system and subsequently introducing additional components in progressing phases. This approach is very useful where the software needs to be modified depending on the outcome of the research work, and the future course of the research depends on the application of the current state of the developed software tool.

Similar analysis and design processes were repeated with the addition of the wind energy conversion systems in the next phase. The results obtained after testing the software were used for comparative research studies. The following phases added diesel generating units and other complexities in a cyclic process until the system included all the components described in the requirement analysis. The sequence diagram for the use-case 'Configure System' and the collaboration diagram for the use-case 'Do Simulation' are shown in Figures A11 and A12 respectively with the addition of wind energy sources.

The addition of new energy sources in the overall generating system necessitated additional creation of classes. The extended generating system interacted with the existing 'System' class which in turn interacted with the existing 'Load' class to represent the entire power system. All of the modifications in the generation extension phases occur in the 'System Component' package while the interaction with the classes in the 'System Operation' package remain unchanged. This was possible by careful assignment of the responsibilities to the existing and new classes.

The interaction between the classes in the modified 'System Component' package is shown in Figure A13. The figure illustrates that the coupling with the storage layer remains unchanged by the modifications since the storage layer interacts only with the classes 'Weather' and 'Load'. The interaction with the presentation layer, however, increases since each of the energy sub-systems have their own interfacing objects that get the corresponding generating unit data from classes in the presentation layer.

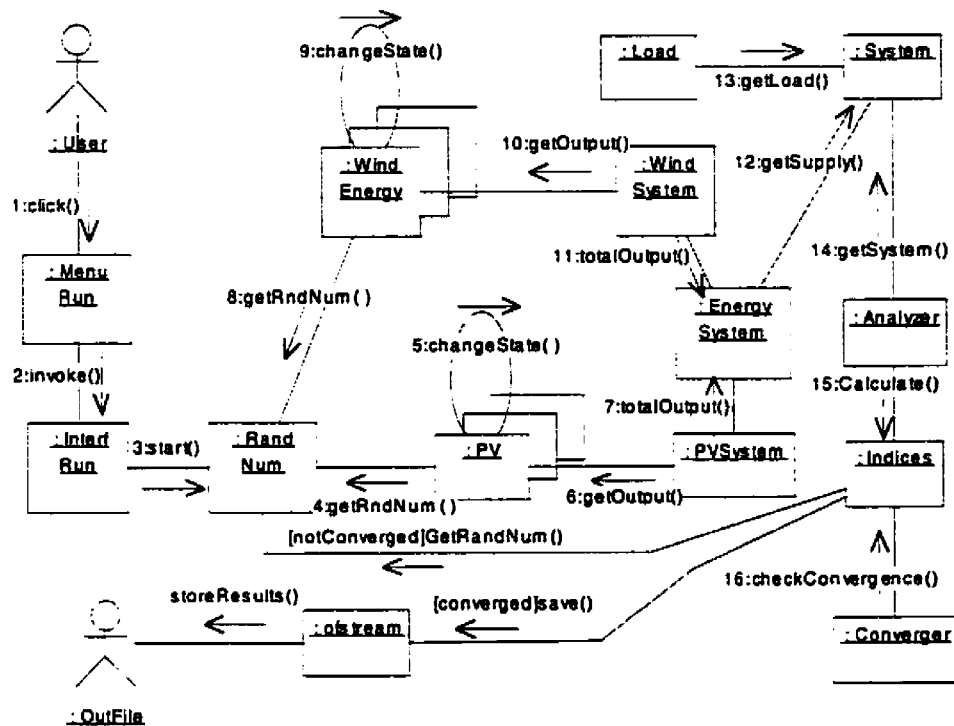


Figure A12: Collaboration Diagram for the Use-case 'Do Simulation' with Wind Energy

The next phase of the development process was to generate the source codes for the entire application and perform necessary testing. Many new features, such as, implementing additional system operating schemes, introducing analysis of energy and cost related indices, providing distribution of the results were implemented in sub-sequent development phases.

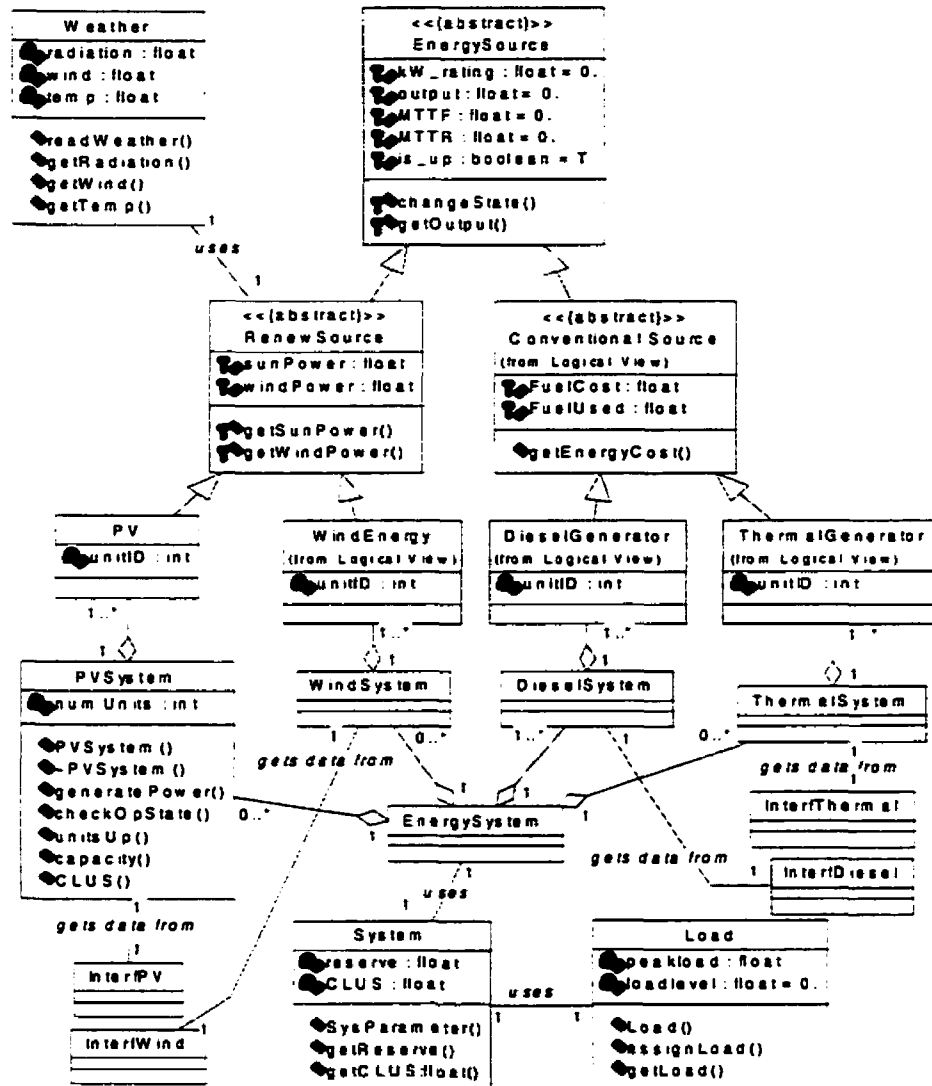


Figure A13: Class Diagram for Modified 'System Component' Package

The software life-cycle can continue for further development by looping back to requirement analysis to incorporate additional requirements and by conducting subsequent analysis, design, programming and testing.

APPENDIX B: USER'S MANUAL FOR SIPSREL+

B1. Introduction

SIPSREL+ is a software package developed at the University of Saskatchewan that utilizes probabilistic evaluation techniques to conduct reliability and cost studies on small isolated power systems containing wind and photovoltaic energy sources. It can also be used to assess the cost and reliability impacts PV and wind energy penetrations to larger systems.

The software tool incorporates a graphical user interface (GUI) that generates run-time instructions and error messages to assist the user while operating the software. The GUI assists the user in providing the necessary data in the proper format to run the application programs. The results are displayed in both tabular and graphical forms.

The program is designed to run on an IBM compatible PC with a Windows compatible display. It has a minimum requirement of an 80486 microprocessor and 4 MB of memory. It requires 4 MB of hard disk memory for storage. The operating system required is a Windows 3.1 or a later version.

SIPSREL+ utilizes Monte Carlo simulation (MCS) to conduct conventional probabilistic risk analysis, system well-being analysis and cost related energy analysis of a power system containing renewable energy sources. The program can provide useful system indices that can be used in a wide range of cost and reliability evaluation of a composite SIPS that can contain different combinations of PV, wind and conventional energy generating sources.

B2. Getting Started

B2.1 Installing SIPSREL+

1. Insert the **Installation Disk** into your computer's disk drive.
2. Run the **SETUP** program in the **Installation Disk**.
3. A Dialog Box will appear inquiring if you wish to **Continue** or **Exit Setup**. If you wish to install SIPSREL+ in another drive or directory (folder) other than the default path of **C:\SIPSPLUS**, you must type in the destination drive and directory in the Command Line Box. Click **Continue**.
4. A message will inform you when the installation is complete. A new program group, SIPSREL+, will appear in the **Program Manager** for Windows 3.1 users. You can drag the SIPSREL+ icon to your **Desktop** if have Windows 95 or a later operating system.

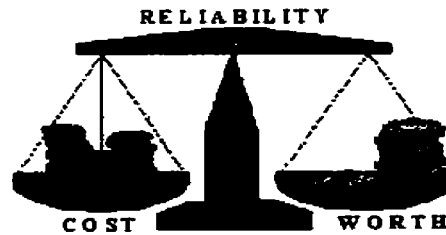
B2.2 Starting SIPSREL+

1. Double click the **SIPSREL+** icon from the **Program Manager** (Windows 3.1) or from the **Desktop** (Windows 95/98). Windows 95/98 users can also launch the program from the **Start Menu** at the bottom left corner of the computer screen. The SIPSREL+ application can be found in the Programs/SIPSREL+ taskbar selections.
2. The application starts with an introductory display as shown in Figure B1.
3. The Main Window will then appear as shown in Figure B2.

You can exit from SIPSREL+ at any time by clicking the **Exit** button. You must follow the instructions provided at the top of the Main Window to carry on with the system evaluation.

SIPSREL+

(Composite SIPS Reliability)



*Created by: Rajesh Karki and Roy Billinton
Power Systems Research Group*

Copyright © 2000 University of Saskatchewan

Figure B1: Introductory Display

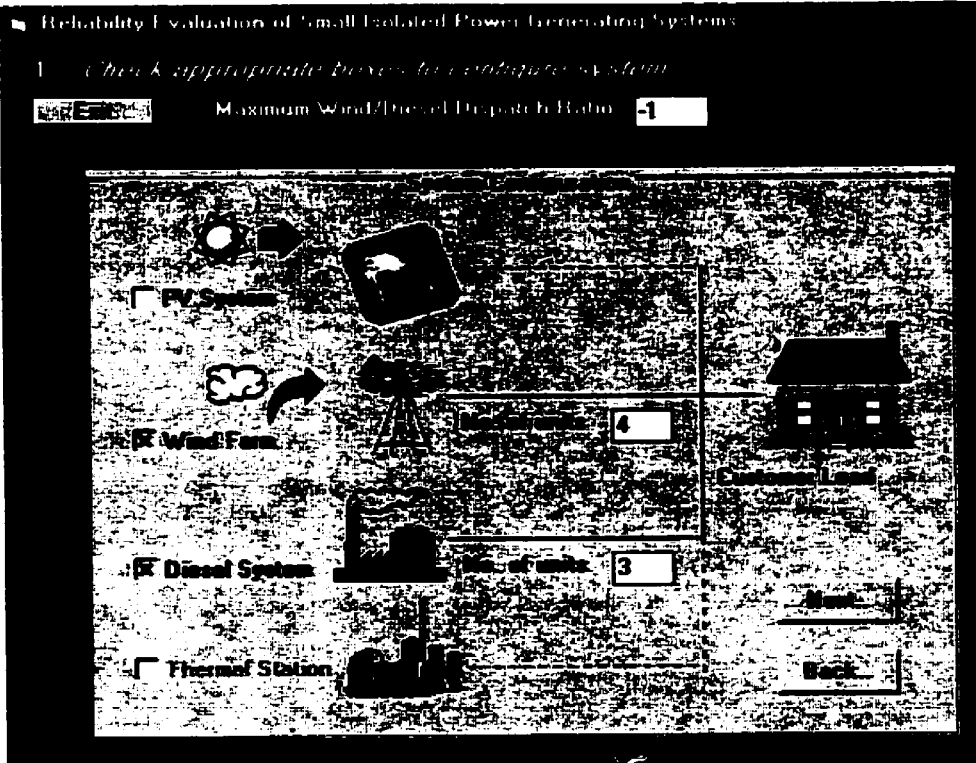


Figure B2: Main Window

B3. System Evaluation

SIPSREL+ provides instructions at the top of the Main Window to facilitate a step-by-step evaluation process. You must follow the instructions requested in each step and then click the **Next** button to continue to the next step. You can always click the **Back** button at any time to return to the previous step. The following sub-sections describe the evaluation procedure.

B3.1 Configure System

1. The first instruction reads “1. *Check appropriate boxes to configure system*”. You must check one or more boxes to select **PV System**, **Wind Farm** and/or **Diesel System** in the **System Configuration** frame.
2. A text-box to enter the number of energy generating units will appear for each energy source you select. Enter the number of units in the corresponding text-boxes.
3. You can specify the operating constraint for wind energy dispatch for stability requirement. A text-box labeled **Maximum Wind/Diesel Dispatch Ratio** will appear when you configure a system containing both the wind and diesel sources. You should enter the specified ratio in the text-box. The default value “-1” indicates that the consumption of wind energy is not restricted by any constraint.
4. Click the **Next** button to proceed to the next step.

B3.2 Input Data

The software tool will instruct you when and what data you must provide to simulate the power system that you have configured. Some data must be entered directly into the data entry forms generated by the program, whereas, other data should be provided in data files that are accessed by the program. You must select the proper files from the list.

B3.2.1 Weather Data

The second instruction reads “2. Click weather icons to get site specific weather data”. You must provide weather data separately for the PV system and the wind farm that exist in the configured system.

1. Click the **Sun Icon** if the configured system includes PV. A dialog box for monthly mean weather data appears on the screen as shown in Figure B3.

	Jan	Feb	Mar	Apr	May
Wind Speed (m/s)	20	23	22	22	22
Temperature (deg)	-13	-9	-4	-1	0
Radiation (kWh/m2)	4.95	8.58	13.55	16.1	21.6

Change Data

Temperature (deg)

4.3

Site Latitude

50.3

OK Cancel

Figure B3: Dialog Box for Monthly Mean Weather Data

2. Select the appropriate data file from the list of files. Click the **View** button to view the contents of the file in the table.
3. Click on any data you wish to change. The selected data will appear in the text-box in the **Change Data** frame. Click the **Change** or **Cancel** button in the **Change Data** frame to confirm or cancel the change respectively.
4. You can change the site latitude data directly in the **Site Latitude** text-box if desired.

5. Click the bottom **OK** button when you are satisfied with the data. You should click the **Back** button if you are repeating the evaluation and are satisfied with the data you have selected in the previous run. The dialog box will then disappear.

The following describes the procedure to provide the hourly wind speed data that are required to simulate a system containing WTG units.

1. Click the **Cloud Icon** (represents wind in this case) if the configured system includes a wind farm. A dialog box for hourly wind data appears as shown in Figure B4 on the screen. The dialog box displays two separate lists of data files.

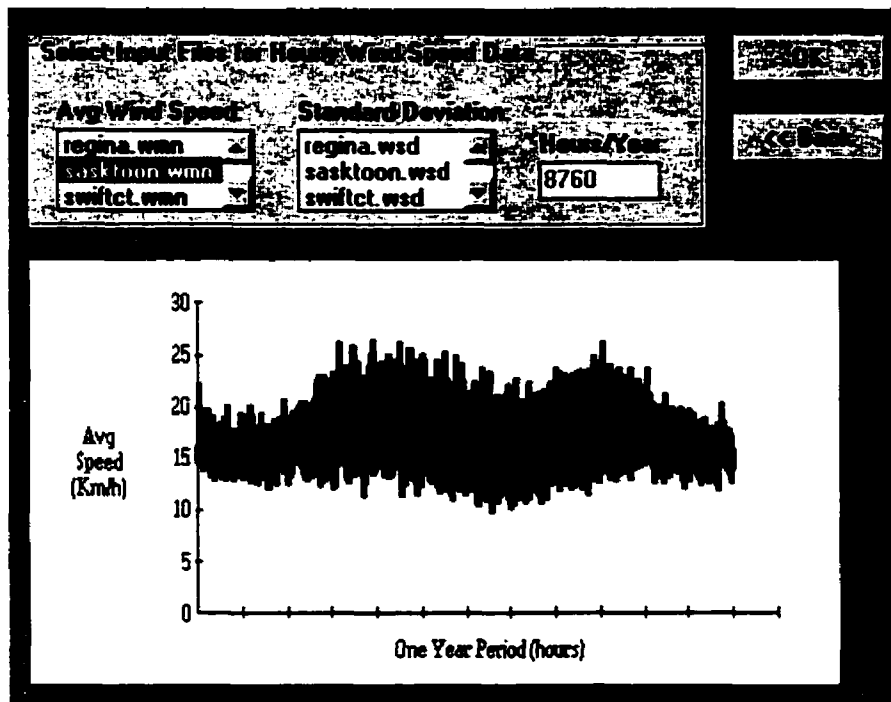


Figure B4: Dialog Box for Hourly Wind Data

2. Click the appropriate files in both the lists to view the data plots. The number of data in each file is shown in the **Hours/Year** text-box.

3. Click the bottom **OK** button to select the data files that you have clicked and highlighted. You should click the **Back** button if you are repeating the evaluation and are satisfied with the data you have selected in the previous run. The dialog box will then disappear.
4. Click the **Next** button to proceed to the next step.

B3.2.2 Energy Generating Unit Data

The third instruction reads “3. *Click energy producer icons to provide system specific data*”. You must provide data separately for the PV arrays, WTG units and the diesel units that exist in the configured system.

1. Click the **PV Icon** if the configured system includes PV arrays. A dialog box for the PV array specification data appears on the screen as shown in Figure B5.
2. Select the appropriate data file from the list of files. A **View** button will appear. Click the **View** button to view the contents of the file in the table.
3. Click on any data you wish to change. The selected data will appear in the text-box in the **Change Data** frame. Click the **Change** or **Cancel** button in the **Change Data** frame to confirm or cancel the change respectively.
4. Click the **OK** button when you are satisfied with the data. You should click the **Back** button if you are repeating the evaluation and are satisfied with the data you have selected in the previous run. A new dialog box for the PV array performance data will then appear on the screen as shown in Figure B6.
5. The number of arrays in the PV system is indicated at the top of the dialog box. Click the **Back** button if you are repeating the evaluation and are satisfied with the data you have selected in the previous run.
6. Click the **New Data** button and enter the ID number, the mean time to failure and the mean time to repair data for the first array.

7. Click the **Next** button and enter the data for the next array repeatedly until the data is provided for all the arrays in the PV system.
8. Click the **OK** button to save the data. The dialog box will then disappear.

Array Make

Select Data File:

- apc-1816.arr
- canrow30.arr
- qs1210.arr

No. of Parallel Groups	
No. of Modules in Series	
Area per Module (m2)	
Tracking Method	
Collector Slope (deg)	
Collector Azimuth (deg)	
Ref Array Op. Temp (C)	
Ref Insolation (W/m2)	
Ref MPP Voltage (V)	
Ref MPP Current (A)	
Ref OCS Voltage (V)	
Ref OCS Current (A)	

<< Back OK

Change Data

Cancel Change

Figure B5: Dialog Box for PV Array Specification

This sub-system has 48 units.

Enter Data (one unit at a time):

Unit ID #	MTF (hours)	MTTR (hours)
1	4380	90

Click Next and enter data for next unit:

New Data Next << Back OK

Figure B6: Dialog Box for PV Array Performance Data

The following describes the procedure to provide the design specification and performance data that are required to simulate a system when it contains WTG units.

1. Click the **WTG Icon** if the configured system includes a wind farm. A dialog box for the WTG specification data appears on the screen as shown in Figure B7.

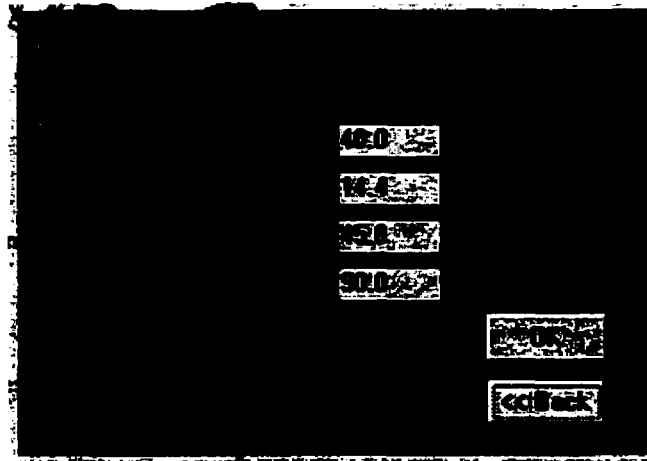


Figure B7: Dialog Box for WTG Specification

2. Default data for the WTG specification is provided in the dialog box shown in Figure B.7. Make any necessary changes and click the **OK** button. You should click the **Back** button if you are repeating the evaluation and are satisfied with the data you have selected in the previous run. A new dialog box for the WTG unit performance data will then appear on the screen similar to Figure B7.
3. The number of WTG units in the wind farm is indicated at the top of the dialog box. Click the **Back** button if you are repeating the evaluation and are satisfied with the data you have selected in the previous run.
4. Click the **New Data** button and enter the ID number, the mean time to failure and the mean time to repair data for the first unit.
5. Click the **Next** button and enter the data for the next unit until data is provided for all the units in the wind farm.

6. Click the **OK** button to save the data. The dialog box will then disappear.

The following describes the procedure to provide the performance data that are required to simulate a system containing diesel units.

1. Click the **Diesel Icon** if the configured system includes a diesel (or a conventional) generating system. A dialog box for the conventional unit data appears on the screen as shown in Figure B8.

This sub-system has 3 units.

Enter Data (one unit at a time):

Unit ID #	kW Rating	MTTF (hours)	MTTR (hours)
1	40	950	50

Click Next and enter data for next unit:

New Data **Next** **OK** **<<Back**

Figure B8: Dialog Box for Conventional Unit Data

2. The number of conventional units in the system is indicated at the top of the dialog box. Click the **Back** button if you are repeating the evaluation and are satisfied with the data you have selected in the previous run.
3. Click the **New Data** button and enter the ID number, the kW rating, the mean time to failure and the mean time to repair data for the first unit.
4. Click the **Next** button and enter the data for the next unit repeatedly until data is provided for all the conventional units.
5. Click the **OK** button to save the data. The dialog box will then disappear.
6. Click the **Next** button to proceed to the next step.

B3.2.3 Load Data

The next instruction reads “4. Click load icon to provide customer load data”. You must provide data in proper format in files for the chronological hourly load and for the composite customer damage function (CCDF).

1. Click the **Load Icon**. A dialog box for load data appears on the screen as shown in Figure B9. The dialog box is divided into two parts; the upper frame lists data files containing chronological hourly load data and the lower frame lists data files containing CCDF data.

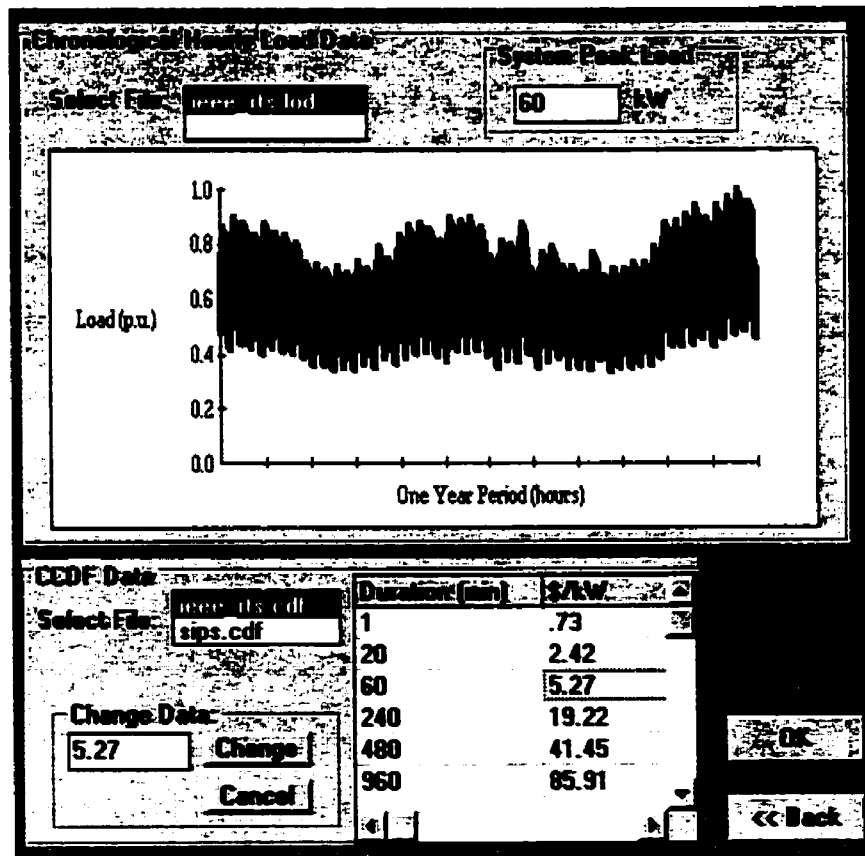


Figure B9: Dialog Box for Load Data

2. Click the appropriate file in **Chronological Hourly Load Data** frame to view the data plot. Enter the system peak load in kW in the text-box.
3. Select the appropriate data file from the list of files in the lower frame for **CCDF Data**. The contents of the file will be displayed in the table.
4. Click on any data you wish to change. The selected data will appear in the text-box in the **Change Data** frame. Click the **Change** or **Cancel** button in the **Change Data** frame to confirm or cancel the change respectively.
5. Click the bottom **OK** button to select the data files that you have clicked and highlighted. You should click the **Back** button if you are repeating the evaluation and are satisfied with the data you have selected in the previous run. The dialog box will then disappear.
6. Click the **Next** button to proceed to the next step.

B3.2.4 Simulation Data

The next instruction reads “5. *Click to provide power system simulation data*”. You must provide data to start and stop the simulation process.

1. Click the **Simulation Data** button. A dialog box for simulation data appears on the screen as shown in Figure B10.
2. Default data are provided in the dialog box to start and stop the simulation as shown in Figure B.10. Make any necessary changes and click the **OK** button. You should click the **Back** button if you are repeating the evaluation and are satisfied with the data you have selected in the previous run. The dialog box will then disappear.
3. Click the **Next** button to proceed to the next step.

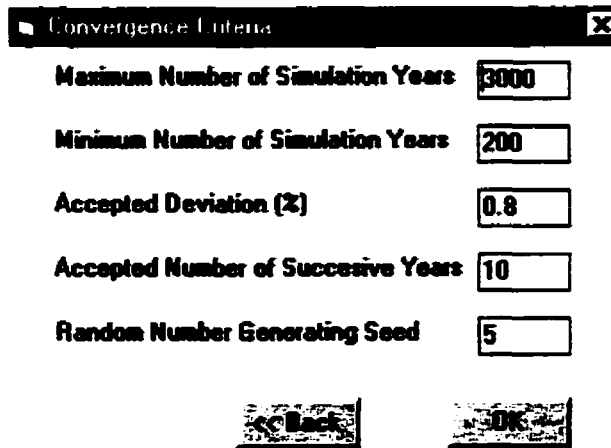


Figure B10: Dialog Box for Simulation Data

B3.3 Run Simulation

At this stage all the necessary input data in the proper format have been provided in order to run the simulation program. The simulation takes considerable amount of time to terminate. It should therefore be confirmed that all the data provided are correct before starting the simulation program. The next instruction reads "6. *Click to run program*".

1. Click the **Run Program** button. The simulation program executes in the DOS mode indicating the number of simulation years lapsed as the program progresses as shown in Figure B11. Windows 95/98 users will notice the **DOS icon** appearing on the bottom task-bar of the screen. Click the **DOS icon** to view the simulation run as shown in Figure B11.
2. You can cancel the simulation program execution by pressing **CONTROL-c** while the program is running.
3. The program will inform you when the simulation is complete and the DOS window will disappear.
4. Click the **Next** button to proceed to the next step.

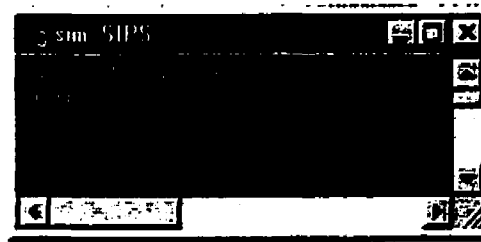


Figure B11: Simulation Run

B3.4 Display Results

The final step is to view the results of the program. The last instruction reads “7. Click to *display results*”. The results include the expected values of the reliability and cost related indices and the associated distributions. The results are saved in data files and can also be viewed in graphical forms.

1. Click the **Display Results** button. A dialog box for output data appears on the screen as shown in Figure B12.
2. Click the **Mean Indices** button in the **Display** frame to display the expected values of the indices listed in the table. Click the down arrow in the right scroll bar to see the contents in the lower part of the table.
3. Click the **Distribution** button in the **Display** frame to view the distribution plots of the indices listed in the table. A new window for distribution plots will appear in the screen as shown in Figure B13.
4. Select an index from the drop-down list box to view the distribution of the index about the mean value. Click the **View** button. The distribution plot will appear. The mean value, the number of simulation years and the name of the output file containing the distribution data for the selected index will appear above in the text-boxes above the plot. The left portion of the computer screen will display the distribution results in a tabular form.

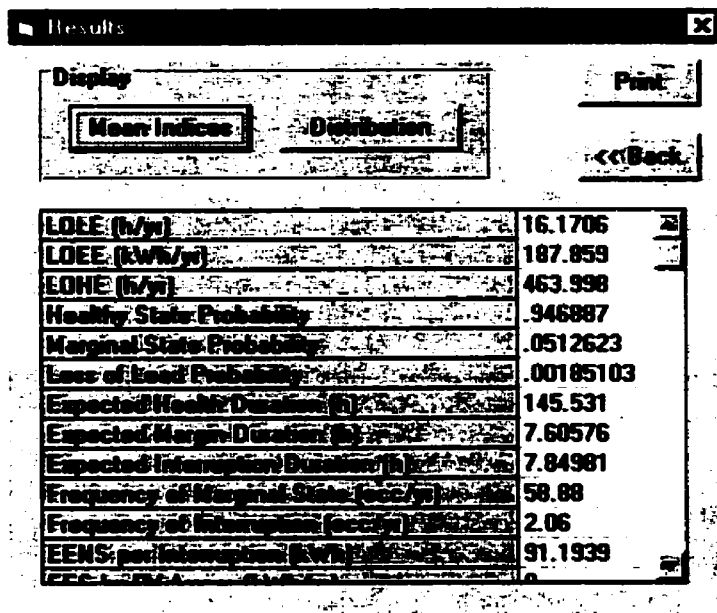


Figure B12: Dialog Box for Output Data

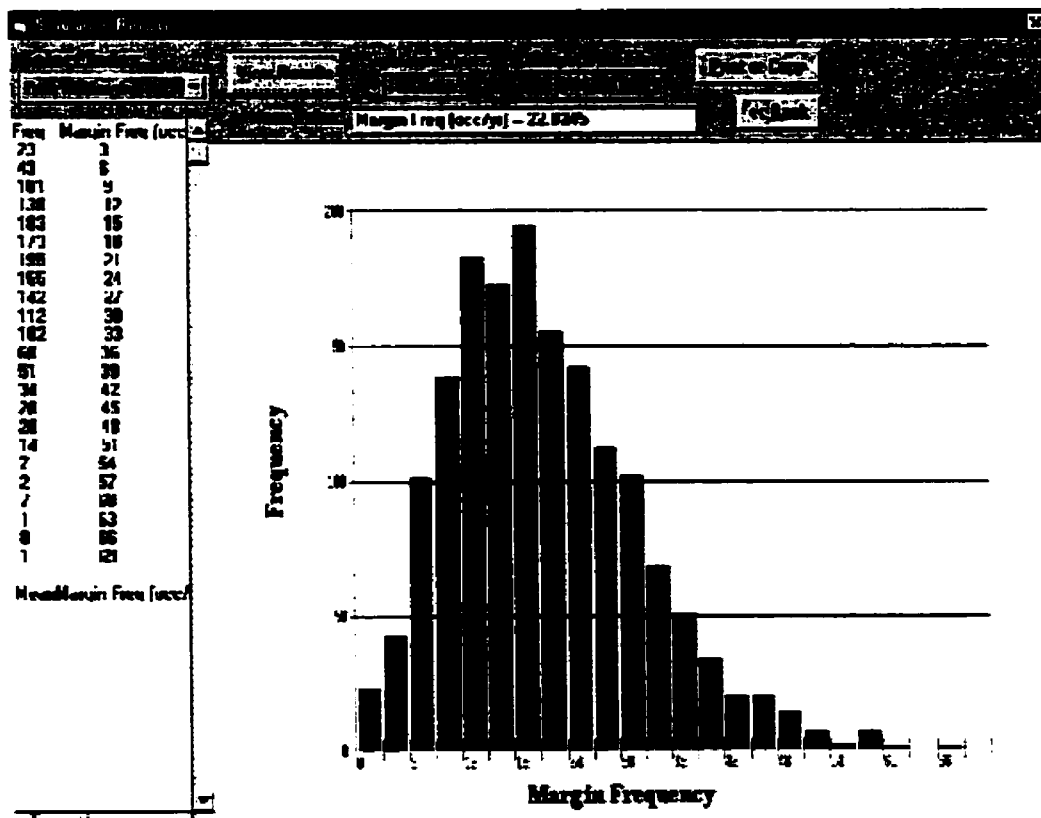


Figure B13: Window for Distribution Plots

B4. Input Data Format

The user-interface assists in arranging the data in the proper format required to run the engine application without causing any file handling errors. The input data is provided in two different ways; by direct entry into the interface forms, and through data files. The GUI program will generate intermediate text files with “.GUI” extension, and will be used by the engine application.

The GUI program will automatically create data files in the proper format when the data is entered directly into the interface forms. The data that are provided by selecting the appropriate data files must however be arranged in the proper format for the program to run without encountering any errors.

You can create your own data files and save them in the application folder. You must use the proper naming conventions as explained later. The files will be displayed in the appropriate lists for you to select as described in Section B3. There are six different types of input data files used by SIPSREL+, which can be grouped into large files and small files. The large data files are handled differently from the small data files. The format of data in the different files are described in this section.

B4.1 Large Data Files

The data files containing the hourly data for the period of one calendar year (i.e. mean wind speed, wind speed standard deviation and load data) are grouped into the large data files category. The contents of the large files are write-protected by the GUI, and can only be viewed in graphical forms. The intermediate “.GUI” files created by the GUI program will only contain the selected file names, and the engine application will directly use the original files.

The files with extensions “.WMN” and “.WSD” contain site specific hourly mean wind speed and hourly standard deviation data for a period of one calendar year. Each row in either data file has 24 columns of data for each hour of the day. The first row contains the data for the first day of the calendar year. There are 365 rows of data for each day in the year.

The data file that contains the chronological hourly load data must have a file name with an extension “.LOD”. The first row in the data file contains an integer number for the number of hourly data points in the file. Each following row contains an hourly load in per unit of the system peak load starting from the first hour in the calendar year.

B4.2 Small Data Files

The files for the monthly mean weather data, PV array specification and CCDF data are grouped into the small data files category. The contents of the small data files are displayed in tables in the user interface. Although the data in the files are write-protected by the GUI, any data displayed in the table can be changed as desired. The GUI program creates a copy of the original data file with the changes made in the table. The copy file, which has a “.GUI” extension, is used by the engine application.

The data file for the monthly mean weather data has a “.WTH” extension in its file name. The first line in the data file contains heading texts. The second line contains the site latitude in degrees. The next 12 rows have three columns of monthly mean data (wind speed in km/h, ambient temperature in centigrade scale and global horizontal irradiation in MJ/m² respectively) starting from January to December.

The data file containing the PV array specification data has an extension “.ARR”. The first line contains texts specifying the make of the PV module. The next 14 lines contain the following specification data per line:

1. Number of Parallel Module Groups
2. Number of Modules in Series
3. Area per Module (m^2)
4. Tracking Method (this data is discarded by SIPSREL+)
5. Collector Slope (deg)
6. Collector Azimuth (deg)
7. Reference Array Operating Temperature (C)
8. Reference Insolation (W/m^2)
9. Reference MPP Voltage (V)
10. Reference MPP Current (A)
11. Reference O.C. Voltage (V)
12. Reference S.C. Current (A)
13. Array Lead-in Resistance (ohm)
14. Wind Speed Correction Factor

The last 8 lines contain energy conversion coefficients described in Reference [42].

1. ALPHA (1/C)
2. BETA
3. GAMMA (1/C)
4. Cell Absorptance
5. Front Panel Emmissivity
6. Panel Transmittance (visible)
7. Panel Transmittance (infrared)
8. Back Panel Emmissivity

The CCDF data is provided in a file with an extension “.CDF”. The first line in the data file contains heading texts. The second line contains an integer indicating the number of rows of data available. Each following row contains two columns of data; an integer for the minutes of interruption followed by the \$/kW cost of that interruption.

B5. Output Results

SIPSREL+ evaluates different types of system indices that are useful for the reliability and cost analysis of the system configured by the user. The indices can be grouped into the following categories:

1. Conventional Risk Indices

The conventional risk indices are the most widely used reliability indices in the generation adequacy evaluation of large interconnected systems. The basic indices and the frequency and duration indices obtained by the software tool are listed below:

LOLE (h/yr)

LOEE (kWh/yr)

Expected Interruption Duration (h)

Frequency of Interruption (occ/yr)

2. Well-being Indices

The system well-being analysis by SIPSREL+ uses the Loss of the Largest Unit (LLU) deterministic criterion. The basic indices and the frequency and duration indices obtained by the software tool are listed below:

LOHE (h/yr)

Healthy State Probability

Marginal State Probability

Loss of Load Probability

Expected Health Duration (h)

Expected Margin Duration (h)

Frequency of Marginal State (occ/yr)

3. Energy and Cost Indices

Most of the energy-based indices listed below are new indices developed to provide realistic evaluation of the benefits from renewable energy sources in a composite SIPS. The user can refer to Chapter 3 of the thesis for further information on these indices.

EENS per Interruption (kWh)
EES by PV Arrays (kWh/yr)
EES by Wind Farm (kWh/yr)
EES by Diesel Units (kWh/yr)
Expected Surplus PV Energy (kWh/yr)
Expected Surplus Wind Energy (kWh/yr)
Expected Unused Diesel Energy (kWh/yr)
Unused Energy Ratio (PV) (%)
Unused Energy Ratio (wind) (%)
IEAR (\$/kWh)
Customer Cost(\$)

SIPSREL+ generates the expected values and the distributions of all the indices listed in the three categories. The user can select any one index at a time to view the results in the **Window for Distribution Plots** (shown in Figure B14). The output data for each index are saved in a separate file with an extension “.OUT”. The name of the file is displayed above the plot in a text-box labeled **Output Data File**. These files are saved in the application folder.

The output data files contain numerical output data but no graphs. The user can copy the graphs and paste them in another application, such as a word processor, for hard copy of the graphs as described in the procedure in Section B3.4.

APPENDIX C: SAMPLE DATA

C1. Introduction

Composite SIPS reliability/cost evaluation requires reliable site specific data. Data from different sources were used to obtain the results for the selected examples presented in this thesis. Most sample data used in the various system analyses are already described in the main body of this thesis. The data used from data files, and referred to this appendix for details, are described here.

The contents of the data files used in the example systems described in this thesis are illustrated in this appendix. The proper data formats required by SIPSREL+ in the different data files are explained in Section B4 of Appendix B. SIPSREL+ setup disk contains all the input data files used in the sample studies presented in this thesis.

C2. IEEE-RTS Data

The IEEE Reliability Test System [45] has 32 conventional generating units with the capacity ratings and the performance data as shown in Table C1. The system peak load is 2850 MW. The chronological hourly data in per unit of the peak load is available in a data file named "IEEE_RTS.LOD". Only a part of the contents of the file is shown in Table C2, since the file size is too large to show all the contents. A plot of the hourly load data is, however, shown in Figure C1.

Table C1: The IEEE-RTS Generating System Data

Rating (MW)	No. of Units	FOR	MTTF (hour)	MTTR (hour)
12	5	0.02	2940	60
20	4	0.10	450	50
50	6	0.01	1980	20
76	4	0.02	1960	40
100	3	0.04	1200	50
155	4	0.04	960	40
197	3	0.05	950	50
350	1	0.08	1150	100
400	2	0.12	1100	150

Table C2: Contents of the File "IEEE_RTS.LOD"

```

8736
0.5371
0.5050
0.4810
0.4730
...
...
0.5783

```

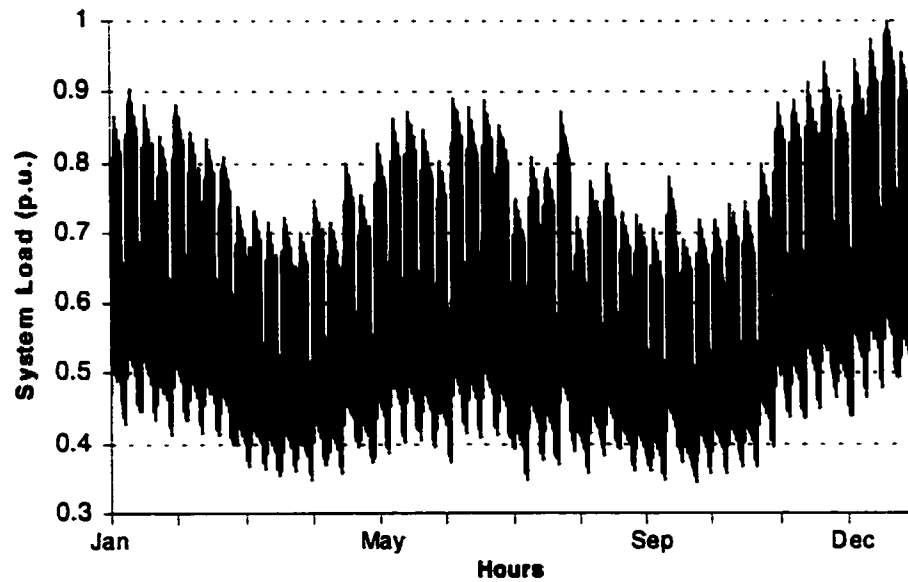


Figure C1: Plot of the IEEE-RTS Hourly Data

C3. Sample Data for PV Systems

Weather data obtained from Environment Canada were used to illustrate the PV system studies in this thesis. The monthly mean wind speed, ambient temperature and global irradiation data for sites in Toronto and Swift Current are available in data files "TORONTO.WTH" and "SWIFTCT.WTH" and shown in Tables C3 and C4 respectively.

Table C3: Contents of the File "TORONTO.WTH"

Toronto: Col.1=WindSpeed(Km/h) Col.2=Temp(C) Col.3=Radiation(MJ/m2)		
43.4		
23.8	-3	5.2
23.4	-3	8.2
22.3	0	12.0
20.9	6	16.1
16.9	12	19.8
14.8	17	21.9
13.3	18	21.9
13.7	17	18.7
15.5	15	14.0
16.2	10	9.2
20.9	4	4.8
23.4	-1	3.9

Table C4: Contents of the File "SWIFTCT.WTH"

Swift Current: Col.1=WindSpeed(Km/h) Col.2=Temp(C) Col.3=Radiation(MJ/m2)		
50.3		
24	-13.0	4.95
23	-9.6	8.58
22	-4.0	13.55
22	4.3	18.01
22	10.8	21.26
21	15.6	23.39
18	18.3	24.24
18	17.6	20.19
20	11.4	14.04
22	5.5	9.29
22	-4.0	5.19
24	-10.8	3.78

PV module specification data were obtained from the Watsun Simulation Laboratory. Data for two different makes of PV modules used in the sample studies are available in data files "PS94T.ARR" and "CANROM30.ARR". The contents of the two files are shown in Table C5.

Table C5: Contents of the Files "PS94T.ARR" and "CANROM30.ARR"

File "CANROM30.ARR"	File "PS94T.ARR"
Canrom, Canrom-30, 30Wp	Nukem PS94T, 94 Wp
1.00000000E+00	1.00000000E+00
1.00000000E+00	1.00000000E+00
4.21000000E-01	9.40000000E-01
1.00000000E+00	1.00000000E+00
6.00000000E+01	6.00000000E+01
0.00000000E+00	0.00000000E+00
2.50000000E+01	2.50000000E+01
1.00000000E+03	1.00000000E+03
1.60000000E+01	3.70000000E+01
2.00000000E+00	2.50000000E+00
1.95000000E+01	4.89000000E+01
2.60000000E+00	2.70000000E+00
6.00000000E-02	6.00000000E-02
1.00000000E+00	1.00000000E+00
2.50000000E-03	2.50000000E-03
5.00000000E-01	5.00000000E-01
2.90000000E-03	2.90000000E-03
9.00000000E-01	9.00000000E-01
9.50000000E-01	9.50000000E-01
9.50000000E-01	9.50000000E-01
9.00000000E-01	9.00000000E-01
9.00000000E-01	9.00000000E-01

C4. Sample Data for Wind Systems

Wind speed data for different locations were obtained from Environment Canada and used in wind energy system studies. Chronological hourly mean wind speed data for North Battleford, Yorkton, Saskatoon, Regina and Swift Current were used in the case studies presented in this thesis and are available in data files "N_BAFORD.WMN", "YORKTON.WMN", "SASKTOON.WMN", "REGINA.WMN" and "SWIFTCT.WMN".

respectively. The hourly standard deviation from the mean for the five locations are available in the files "N_BAFORD.WSD", "YORKTON.WSD", "SASKTOON.WSD", "REGINA.WSD" and "SWIFTCT.WSD" respectively. These data files are automatically loaded while installing SIPSREL+ and are not shown here. The hourly mean wind speed data for the five locations are however plotted in Figures C2 – C6.

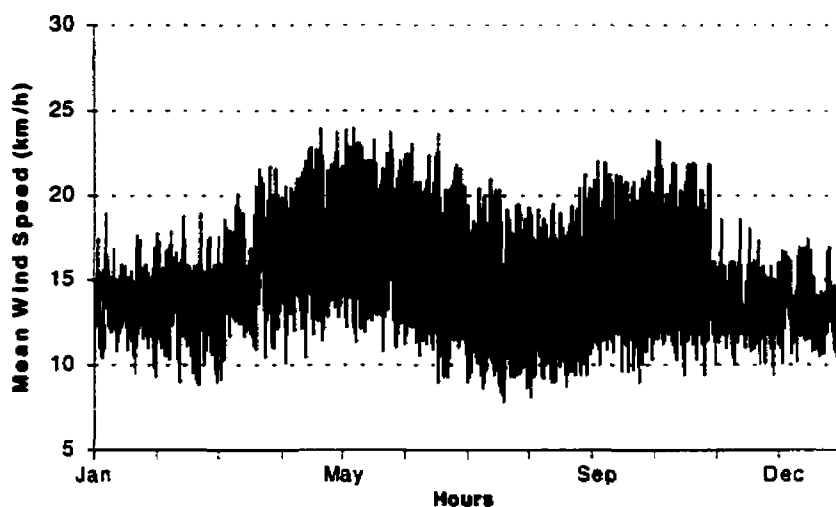


Figure C2: Mean Wind Speed at North Battleford

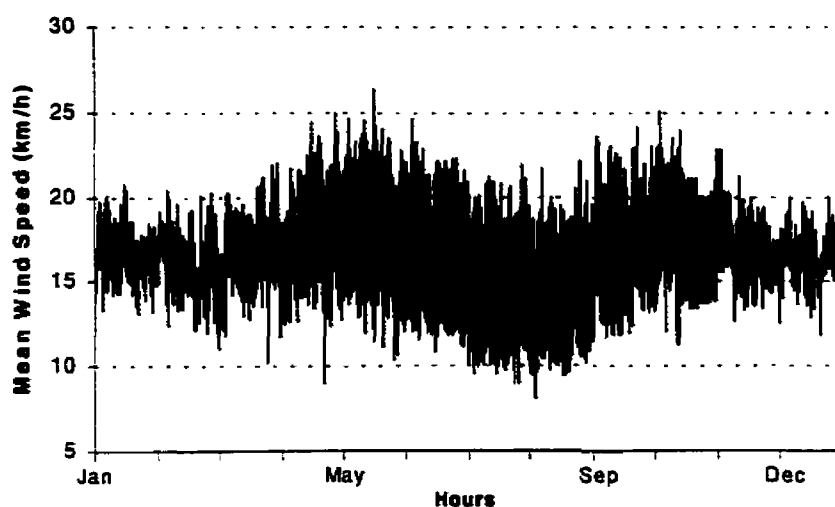


Figure C3: Mean Wind Speed at Yorkton

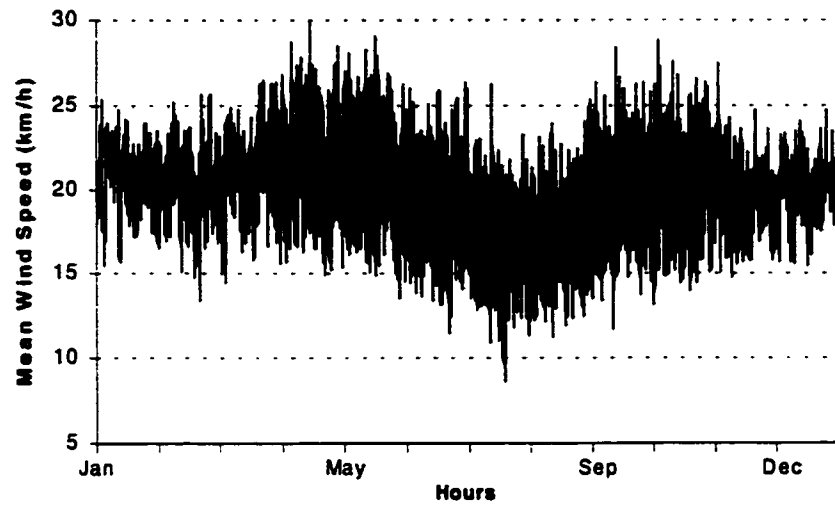


Figure C4: Mean Wind Speed at Saskatoon

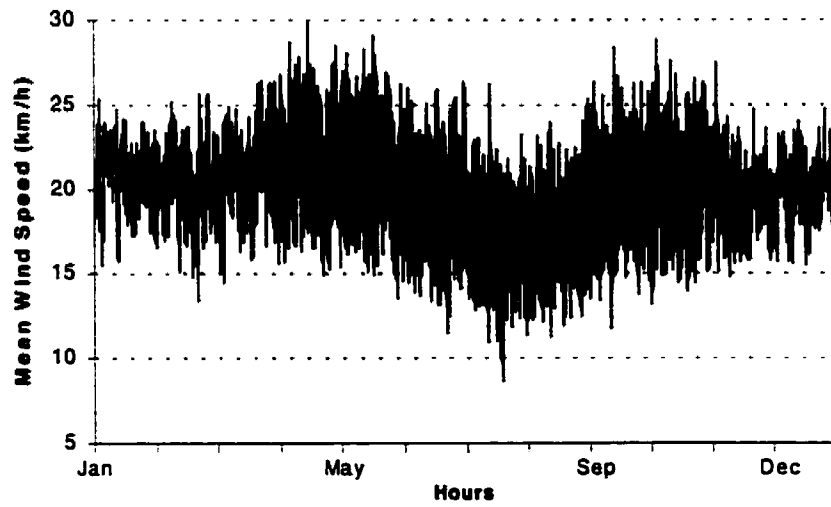


Figure C5: Mean Wind Speed at Regina

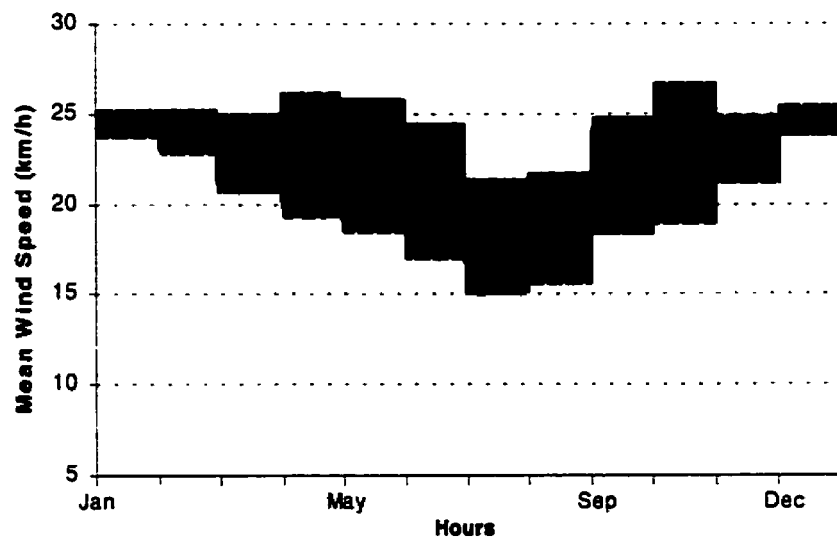


Figure C5: Mean Wind Speed at Swift Current

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